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ABSTRACT

Use of Impervious Covers and Carbon Adsorption for

the Control of Leachate Production in Municipal

Municipal Landfills (May 1979)

Richard Charles Carmichael, B.S., University of

Texas at Austin

Chairman of Advisory Committee: Dr. Harold Wolf

The most popular method for the disposal of solid wastes in the
United States is by landfill. A proper landfill, termed sanitary
landfill, is one which is located, designed, and operated to minimize
or eliminate environmental impact. One potential environmental impact
is contamination of ground- and/or surface water. The potential for
contamination exists because within a land disposal site various physical,
chemical, and biological processes occur which produce compounds that
can be dissolved or suspended in water. Water thus contaminated is
termed leachate.

There are two and possibly three stages of leachate production
in a land disposal site. The first leachate production arises from
the compression and compaction of the solid wastes. The second leachate
production is due to water produced during decomposition. The third
and by far the most significant stage of leachate production is due
to water infiltration.

A comprehensive literature review was performed to determine if
water-impervious (but gas-permeable) covers could be employed to prevent

water intrusion and thus stage 3 leachate production in sanitary land-
fills. The costs and advantages/disadvantages of covering a landfill
to prevent water intrusion versus lining a landfill to collect and
treat stage 3 leachate were compared. Basically the prevention of
stage 3 leachage production appeared the most practical engineering
approach.

Next the changing composition of municipal refuse was investigated
to determine if stage 1 and stage 2 leachate production would continue
to be a problem. The literature search indicated a trend toward an
increased moisture content of municipal solid wastes and thus a con-
tinuation of production of stage 1 and stage 2 leachate.

The final phase of the research centered on the use of granular
activated carbon for the control of stage 1 and stage 2 leachate.
Both equilibrium and column tests were performed using a sample of
young leachate. The results of the study indicated that the use of
a carbon lining for the control of stage 1 and stage 2 leachate in a
sanitary landfill is feasible. An example showing the amount of carbon
required to line a theoretical sanitary landfill is included. The
author concludes with a comparison that shows the chemical oxygen demand
attenuation of granular activated carbon to be better than that of three
clay minerals.

USE OF IMPERVIOUS COVERS AND CARBON

ADSORPTION FOR THE CONTROL

OF LEACHATE PRODUCTION IN

MUNICIPAL LANDFILLS

A Thesis

by

RICHARD CHARLES CARMICHAEL

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

May 1979

Major Subject: Civil Engineering

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CHAPTER I

INTRODUCTION

> In no branch of municipal service has so little prog-
> ress been made in the United States as in the disposal
> of garbage. Why do such conditions exist? First, because
> the sanitary collection and disposal is appreciated neither
> by the general public nor the city officials; second,
> because it is seldom recognized that the problems incident
> to final disposal are largely engineering in character
> and therefore should be entrusted to engineers. [1,2]

The above quote could have come from any recent hearing or meeting

concerning solid waste management. Instead it came from a paper read

by Mr. W. N. Baker before the League of American Municipalities in 1901.

The basic problems associated with solid waste disposal have not changed

materially over the years, but their magnitude has increased enormously.

The potential for solid waste to pollute ground and surface waters is

just now being appreciated, and groundwater pollution presents a very

serious problem. Once contaminated, a groundwater aquifer may remain

so for decades. Considering the fact that almost half the population

of this country depends on groundwater (and this number is increasing)

any potential threat to this resource must be investigated. [3]

Review of Previous Research

When water is allowed to percolate through solid wastes, it entrains

various dissolved and suspended matter and microbial waste products.

Water thus contaminated is termed leachate. [4] Depending upon the

The format and style of this thesis follows that of the Journal of the
Water Pollution Control Federation.

circumstances, leachate has the potential to pollute ground and/or surface waters. The phenomenon of potential leachate pollution has only recently received recognition. The Office of Solid Waste Management Programs and Office of Water Supply reported to Congress in 1976 that: "Waste disposal practices have contaminated groundwater on a local basis in all parts of the nation and on a regional basis in a few heavily populated and industrialized areas."[5] This statement is probably accurate, although there were few well-documented reports of leachate groundwater pollution found in the literature, the main reason being that monitoring of potential sources of groundwater contamination is almost nonexistent.[5]

Classical groundwater monitoring has been concerned primarily with bacteriological contamination; few chemical analyses were performed. Generally, it is not until after gross pollution of a water source had occurred, resulting in complaints, that an investigation is undertaken. However, the Environmental Protection Agency has found that, "for every waste disposal facility documented as a source of groundwater contamination, there are thousands more which are sited, designed, and operated in a similar manner."[5]

The magnitude of potential pollution problems associated with solid wastes can be appreciated when it is noted that the population of this country produced 250-million tons of residential, commercial, and institutional solid wastes in 1969. This was in addition to the estimated 110-million tons of industrial wastes and nearly 4-billion tons of mineral and agricultural wastes generated. Over ninety percent of this was disposed on land and most of it incorrectly.[4] Solid waste generation in this country will not decline in the near future and governmental

programs aimed at reducing the volume of solid wastes have not proven
successful. In fact, the federal government estimates that per capita
solid waste for urban areas will rise from 5 pounds in 1970 to 8 pounds
in 1980.[4] In addition, the pollutants scrubbed from our air and water
under the Clean Air Act, the Water Pollution Control Act, and other
federal and state laws concerning public health and environmental pro-
tection have and will continue to generate great amounts of solid
wastes.[6]

By far the most popular method for disposal of these solid wastes
is landfill. The basic disposal method of burying solid waste has
seen little change since about 1900.[7] Until recently little attention
has been paid to groundwater intrusion of surface water (including
precipitation) percolation into landfill cells. However, new federal
guidelines have been enacted requiring landfills to be constructed with
impervious liners to prevent intrusion and catch percolation (generally
for some form of later treatment).[8] However, capturing percolation
for treatment appears to be backwards. It is believed that landfills
could be provided with impervious covers that would prevent percolation
and consequently, groundwater pollution.

Purpose and Scope

The objectives of the proposed research were as follows:

I. To review the literature to determine the prospect of employing
a final water-impervious (but gas-permeable) cover over a sanitary
landfill as a means of preventing long-term (stage-3) leachate production.

II. To investigate the composition of the initial (stage-1 and stage-2) leachate produced to determine if carbon adsorption would provide a feasible means of control.

III. To determine by reviewing the literature if the changing composition of municipal refuse would alter initial leachate production.

The research plan consisted of:

I. A literature search to investigate the utility of employing a final water impervious cover over a landfill site.

II. A literature search to investigate the changing composition of municipal refuse as it relates to initial leachate production.

III. Four visits to a closed city landfill to obtain leachate samples for the study.

IV. Laboratory tests on leachate including biochemical oxygen demand tests, and carbon equilibrium and column tests.

V. Evaluation of the data and interpretation of the results.

VI. Determination of the amount of carbon required to control initial leachate production.

VII. Comparison of leachate COD attenuation by activated carbon versus the leachate COD attenuation of three clay minerals.

CHAPTER II

LITERATURE REVIEW

The purpose of this chapter is to acquaint the reader with the problems of solid waste disposal and leachate pollution. This chapter consists of five sections: (1) History of Solid Waste Disposal, (2) Leachate Production from Solid Waste, (3) Prevention of Leachate Pollution, (4) Control of Leachate Production, and (5) Changing Composition of Municipal Refuse.

History of Solid Waste Disposal

Mankind has generated solid wastes since before recorded history. Cavemen littered the landscape with their unwanted materials.[9] The Bible records that Moses enjoined his people to carry all offensive matter outside of camp and burn it.[1] The American Indians moved from place to place in part to escape their solid waste problems.[9] In Asia garbage was thrown out into the fields to be eaten by scavengers.[1] Medieval Europeans heaved all non-decomposable and inoffensive waste into low areas or on to the streets.[1,9] Some of the streets in the oldest European cities have been raised several feet over the centuries as a result of the refuse dumped upon them.[1] Colonial Americans disposed of small waste materials by dropping them down the privy. Larger unwanted items were simply carted off to the woods a discrete distance from dwellings and abandoned.[9]

The haphazard disposal of solid wastes in the United States saw little national interest until 1887, when the American Public Health Association appointed a Committee on Garbage Disposal to study the solid

waste problem. The Committee issued reports from 1888 to 1897 on methods of garbage disposal. Sanitary aspects of solid waste disposal were given first priority in all Committee reports. The final report from the Committee on disposal methods in the United States recommended the following: "Feeding to swine, dumping on land or into large volumes of flowing water, plowing into soil, extracting grease, or cremating the organic matter." In regard to the method best suited for a given city, the Committee recommended that the method that could be implemented at the least expense be employed.[1]

The actual disposal of solid wastes remained haphazard until the late 1800's/early 1900's. Up to this time the collection and disposal of solid wastes was viewed as a personal problem. Individuals either allowed their solid wastes to accumulate in their yard (or surrounding area) and then, when the pile became a nuisance, hauled them away (usually to the nearest open lot), or they made arrangements with private scavengers (who generally dumped the solid wastes on open land without proper public regulation).[1] In either case problems of public health and nuisance were created.[10] As a result the public began to demand that municipal governments provide garbage collection service in order to protect the community from the nuisances of solid wastes.[11] In response to public pressure and recommendations from State Boards of Health, states began enacting laws to enable towns to levy a special tax for the collection and disposal of solid wastes.[1]

Unfortunately, the emphasis on solid waste management centered on collection rather than disposal. Disposal methods for solid wastes continued to be: dumping into large bodies of water, dumping onto land, filling in low ground (or the sanitary fill), feeding to animals, and

incineration. Dumping into large bodies of water, such as lakes or the sea, proved less than satisfactory because winds and tides often returned floating wastes to shore.[1,10,11] Dumping onto land was widely utilized by cities of all sizes.[11] The filling in of low ground (the sanitary landfill) was considered a pioneer process that could be used as an emergency measure.[10] Feeding to animals, namely swine, was a popular method of garbage disposal. However, the use of swine feeding required the segregation of edible garbage from solid wastes and this generally meant separate collection vehicles. The problem and expense of separation coupled with the danger of trichinosis in garbage-fed swine led to the eventual abandonment of swine feeding as a widely practiced method of garbage disposal.[10] Incineration of solid wastes generate much interest, but has not been widely used.[10,11]

In the operation of early dumps and landfills, refuse was deposited upon open land and allowed to decompose. It soon became apparent that the dumping of garbage alone caused a large fly and rat population to develop. If garbage was not carefully separated from other rubbish then the rats and flies joined the other problems of the open dump, namely odors, airborne litter, and waste paper. These and other reasons caused a change in landfilling operations. Operators in Champaign, Illinois (1904), Columbus, Ohio (1906), and Davenport, Iowa (1916) began burying or covering refuse with earth. The concept of "sanitary land-filling" was first proposed in describing a cut-and-cover refuse operation in Fresno, California, in the 1930's.[6]

Shortly thereafter in 1935 the Sanitary Engineering Division of the American Society of Civil Engineers appointed a Committee on Technical

Aspects of Refuse Disposal. The purpose of this Committee was to "stimulate and develop, by studies, reviews, and discussions of refuse collection and disposal problems, a more adequate and impartial engineering basis for this field of sanitation." After four years in existence, in 1939, the final report of the Committee stated that: "due to the unusual activity of members of the Committee and on account of the lack of general interest in the subject under consideration at the time .... it is recommended that this Committee be discontinued."[12]

It was not until 1959 that the American Society of Civil Engineers published a manual of practice on sanitary landfill. This manual defined the sanitary landfill as: "A method of disposing of refuse on land without creating nuisances or hazards to public health or safety, by utilizing the principles of engineering to confine the refuse to the smallest practical area, to reduce it to the smallest practical volume, and to cover it with a layer of earth at the conclusion of each day's operation or at such more frequent intervals as may be necessary."[13]

The methodology of sanitary landfilling has changed little since the 1900's. Basically there are three variations of refuse placement currently in use in the United States: the trench method, the area method, and the ramp method.

The trench method is generally used on level or gently sloping ground. A long narrow trench is cut into the ground and the soil removed from the excavation is stockpiled. A ramp is left at one end of the trench to allow access by heavy equipment. Solid wastes are deposited beginning at the sloped end of the trench. The waste is spread and compacted on a shallow inclination. The waste is covered at the end of

each day's operation. When the entire trench has been filled it is covered by a thick cover layer (at least two feet in depth).

The area method of sanitary landfilling also utilizes level or gently sloping ground. In contrast to the trench method, solid wastes are dumped directly on the ground. The only prior excavation may be removal of top soil, but this is not a prerequisite. After being dumped, the solid wastes are spread and compacted to a uniform layer by heavy equipment. The compacted solid wastes are covered at the end of each day. Each day's compacted and covered solid wastes becomes a solid waste cell. Cells may be stacked one upon the other raising the area to any desired height. As in the trench method, a thick (two feet or more) final cover is required prior to abandoning the site.

The ramp method is a cross between the trench and area methods that makes better use of some types of tarrain. An existing slope may be cut away and the excavated soil stockpiled. Solid wastes are then deposited against the face of the cut-away slope, spread, and compacted. At the end of each day's operation the solid wastes are covered using the stockpiled soil. The newly covered solid waste cell creates a new slope against which solid wastes can be deposited. This process can be repeated until the landfill runs out of area to fill. Again, a final thick (two-foot minimum) cover layer must be installed prior to abandoning the site.

Sanitary Landfill Problems

The term sanitary landfill has become widely accepted as describing a "proper" operation. The idea that solid wastes are being disposed in a manner so that no hazard to public health or safety is created has led

to a proper belief that sanitary landfilling is the "final disposal method." In other words, the wastes deposited in a sanitary landfill are considered to be ultimately eliminated from the environment.[6,13]

Unfortunately, this is not the case. When water is allowed to percolate through solid wastes, it entrains various dissolved and suspended matter and microbial waste products. Water thus contaminated is termed leachate.[14] Depending upon the circumstances, leachate has the potential to pollute ground and/or surface waters. The phenomenon of potential leachate pollution has only recently received recognition. The Committee on Sanitary Engineering Research, American Society of Civil Engineers, took note in their proceedings paper No. 2874, July 1961, that six percent of the landfill managers answering their questionnaire on sanitary landfill practices reported experiencing groundwater pollution problems.[15] Mr. John R. Snell, F.ASCE, Committee member, included in his written comments that "this percentage is very low, and in all probability the pollution is more likely somewhere between 20% and 50%." The U.S. Public Health Service in a 1969 interim report entitled "Development of Construction and Use Criteria for Sanitary Landfills"[16] and the State of California Department of Water Resources in a 1969 report entitled "Sanitary Landfill Studies"[17] noted that leachate constitutes a potential source of groundwater pollution. More recently, the Office of Solid Waste Management Programs and Office of Water Supply reported to Congress in 1976 that: "Waste disposal practices have contaminated groundwater on a local basis in all parts of the nation and on a regional basis in a few heavily populated and industrialized ares."[5] This statement is probably accurate, although there are few well-documented reports of leachate groundwater pollution

found in the literature, the main reason being that monitoring of potential sources of groundwater contamination is almost nonexistent.[5]

The precise composition of leachate has been the subject of several studies conducted by A. A. Fungaroli,[18] James M. Robertson et al.,[19] Frederick G. Pohland,[20] and Qasim and Burchinal.[21] The results of these studies indicate a wide variation in the composition of leachate. The differences in composition reported by various studies are explained in part by the following factors: age of the landfill and corresponding state of stabilization; composition of the solid waste, the depth of the solid waste cell; the moisture content and amount of infiltration; ambient temperatures; sampling techniques; analytical methods; and the interaction of the leachate sample with its environment prior to collection.[14] There was general agreement, however, among the reports that the gross analysis of leachate contains high concentrations of organic matter and inorganic ions, including heavy metals.

Fungaroli[18] found two and possibly three stages of leachate production in a sanitary landfill. The first leachate production arose from the compression and compaction of the solid waste. The amount depends upon the initial moisture content of the wastes involved. The moisture content will vary with the climatic conditions and the composition of the solid waste. The composition will vary in turn with the population served, the frequency of collection, and the season of the year. Initial leachate production was expected to be a relatively small quantity. The second production would be due to the water produced during decomposition. This amount would be so slight that it might be disregarded. The third and by far the most

significant stage according to Fungaroli[18] was due to water infiltration.
The amount of leachate produced during this stage was directly dependent
upon the amount of water that flowed through the solid wastes deposit.[18]

Water may infiltrate a landfill in several ways. Poor or im-
proper site selection, such as locating a landfill on a swamp or marsh,
placing solid wastes on or below the groundwater table, or placing a
landfill in an active flood plain without proper design will result
in leachate production. Inadequate design that fails to divert upland
drainage, doesn't provide a proper grade or slope for the final cover
to allow for runoff, or fails to specify a cover material with a low
permeability will result in water infiltration and leachate production.
Poor operating procedures with incompetent or inadequately trained
personnel resulting in failure to cover wastes, or wetting wastes to
aid compaction will result in even more leachate production. Even a well-
designed and operated landfill has the potential to produce leachate.[22]
In addition, the potential to produce leachate cannot be limited to
active landfills; abandoned or reclaimed landfills can also produce
leachate when subjected to infiltration.

Prevention of Leachate Pollution

The Federal government under the Solid Waste Disposal Act (Public
Law 89-272) as amended by the Resource Conservation and Recovery Act
(RCRA) of 1976 (Public Law 94-580) has been working with state govern-
ments to eliminate inadequacies in site selection, design, and operating
procedures.[23] These Acts in essence required that no solid waste facil-
ity be operated in the United States without a permit.[24] Through the

permit authority it was anticipated that within the next five years
the existing dumps and landfills will be either closed or upgraded to
minimize or eliminate the potential for leachate pollution.[21] Any
new landfills must meet stringent engineering design criteria aimed
at the prevention of leachate pollution.

After the implementation of engineering controls in the construction
of a waste disposal site the most accessible area for water infiltration
will become its upper surface.[23,26] The amount of infiltration will
depend upon the surface conditions of the landfill and the climatological
characteristics of the site's location.[26] Based upon data from the
United States Weather Bureau, only thirty percent of the continental
United States receives so little rainfall that percolation of water
through the solid waste would not occur.[25] In addition, if the final
use of the landfill was to be a park or agricultural area, irrigation
would be a likely practice in arid and semi-arid areas, leading again
to possible increased infiltration.

There are two schools of thought concerning abatement of ground-
water pollution due to leachate. The first approach is the water
balance method. The basis of this approach is the idea that precipi-
tation, evapotranspiration, surface runoff (from the landfill surface),
and soil moisture storage can be balanced to minimize or prevent perco-
lation of water through solid waste in a landfill.[26] The water balance
method has some application in arid and semi-arid locations, but will
not prevent percolation in the vast majority of areas. Even in those
areas where the water balance method can be shown to prevent percolation
due to rainfall, at least four inches of infiltration must be allowed

per year in order to wash accumulated salts out of the top soil. The four-inch per year infiltration is based upon average irrigation water and is necessary to sustain plant life.[27] Therefore, for the purpose of this thesis the water balance method in sanitary landfill design was viewed as a means of reducing the amount of water infiltrating solid wastes, thus resulting in less leachate. (It should be noted, however, that the leachate produced will be more concentrated.[25]) The water balance method will not be assumed to produce an impervious cover.

The second and most widely practiced abatement approach is to install an impervious liner in a land disposal site so that a "bathtub" can be formed.[8] The purpose of this approach is to catch the leachate, generally for some form of treatment to remove the harmful constituents. The installation of impermeable liners is a relatively new approach, thus little is known regarding their long-term integrity. Leachate presents an extremely hostile environment for liner materials, as well as the compounds used to seal the seams of certain liner types.[8,28] Even materials normally considered inert, such as clays and polymeric membranes, may react with leachate causing liner failure.

Materials considered for lining solid waste disposal sites include: conventional paving asphalts, hot sprayed asphalt, asphalt sealed fabric, polyethylene (PE), polyvinyl chloride (PVC), butyl rubber, Hyalon (a registered trademark of Dupont), ethylene propylene diene monomer (EPDM), chlorinated polyethylene (CPE), compacted clay, and mixtures of native soil with either montmorillonite or cement. All of these materials have been used successfully as pond and/or paving materials. Their application to landfill use has not been proven.

H. E. Haxo and R. M. White,[28] working under an Environmental
Protection Agency grant, constructed twenty-four simulated sanitary land-
fills and exposed the above materials to leachate for a period of one
year. During the one year of exposure all of the materials tested showed
some signs of reaction with the leachate. The hot sprayed asphalt and
paving asphalt both failed (allowed leachate to pass). The admix liner
materials lost substantially in compressive strength. The asphalt
membranes adsorbed leachate to some extent, but otherwise changed little.
The polymeric membranes swelled to varying degrees and lost some of their
tensile strength and hardness, but generally retained their tear and
puncture strengths. The greatest problem experienced was in seam
strengths. With the exception of the heat sealed seams, there was a
significant loss of strength in all seams.[28]

In addition to the problem that the durability and integrity of
liner materials for use in solid waste disposal is unknown, little
effort has been directed toward developing leak detection systems for
sanitary landfills. While leak detection is a relatively minor problem
(existing systems could probably be easily adapted) the repair of a leak
once detected would be a major undertaking. In all probability any
attempted repair of the liner would cause even greater damage.[8]

Should the liner prove successful in producing a bathtub effect,
a new potential problem would be created; that is, when infiltration
exceeds the capacity of the bathtub, it will overflow. When overflow
occurs, surface springs of leachate may be formed which present a
potential source of surface water pollution. To prevent overflow, most

landfills of the bathtub design are sloped to a sump where a pump was provided to remove the leachate either for recycle through the landfill or treatment.

A three-year study by F. G. Pohland[29] on leachate recycle using simulated municipal landfills indicated that leachate recycle accelerated the removal of the readily available organics from the solid wastes and leachate. The removal of readily available organics by leachate recycling was attributed to the rapid development of an active anaerobic population of methane formers. The removal of organics resulted in a more rapid stabilization or "aging" of the experimental landfills.

The use of leachate recycle is not without drawbacks. Recycling leachate does not eliminate the pollution potential of a landfill, it simply reduces the potential by condensing and controlling the initial biological stabilization or aging process. The leaching process can continue for years but the pollution potential will have been greatly reduced.

Also, Pohland[29] points out in his summary and conclusions that recycling leachate may not be sufficient to reduce the pollution potential of leachate to concentrations acceptable for discharge; rather a combination of recycle, separate biological and physical-chemical methods may be necessary.[28]

Two areas not covered in the literature that may cause problems in using the leachate recycling method are containment of the leachate in the landfill (integrity of the liner) and the possibility of concentrating non-degradable toxic or hazardous wastes. Many toxic and

hazardous wastes have been deposited in municipal landfills because they had been considered to be in such low concentrations as to be innocuous. Others may have been deposited because they were not readily recognizable toxic forms (such as polychlorinated diphenyls contained in electronic capacitors, or persistent pesticides, herbicides, or fungicides coated on or saturated into rags, paper, wood, etc.). There was also the continuing disposal of hazardous wastes in municipal land-fills associated with and because of a lack of effective control.[22]

Studies of the treatability of leachate have been relatively recent endeavors.[30] Studies by Boyle and Ham,[31] Thornton and Blanc,[32] Palit and Qasim,[30] Uloth and Mavinic,[33] and Chian and DeWalle[34,35] have indicated that biological treatment of sanitary landfill leachate is effective in removing a substantial portion of the organic pollutants. Of the treatment processes investigated anaerobic treatment was the most promising providing greater than ninety-percent BOD_5 reduction.[31,33,34]

As with the leachate recycle method, anaerobic treatment was not sufficient to reduce the pollution potential of leachate to concentrations acceptable for discharge.[34] Polishing of anaerobically treated leachate through further aerobic biological treatment and/or physical-chemical methods was found to be necessary. Of the physical-chemical treatment methods investigated, chemical precipitation using lime followed by carbon adsorption appeared to give the best results.[34]

There are many problems associated with the treatment of leachate. The most obvious, based on previous discussion, is the liner used to collect the leachate for treatment. Another problem is the leaching of toxic materials from the landfill that either pass

through the treatement system and into the environment or settle out
and become solid waste once more. Since few municipal landfills are
located near municipal sewage treatment plants or systems, treatment
facilities would generally have to be constructed on site. Because
leachate varies greatly from landfill to landfill, even from area to area
and over time within the same landfill, design of one package system
for all landfills (or even the same landfill over time) is impossible.

It is felt that the greatest problem associated with leachate
treatment is that it does not prevent leachate production. It is a
control method that does nothing to alleviate the basic problem.

Control of Leachate Production

The production of leachate may be controlled in basically two
manners. The first would be to control what goes into a landfill.[6]
If the materials placed in a given landfill were limited to only
innocuous materials that never decompose, then no leachate problem would
result. However, disposal in the landfill would be limited to only a very
few waste materials. The nature of ordinary domestic refuse would
prohibit its disposal in such a controlled landfill. Obviously then,
attempting to control leachate by controlling materials deposited has a
most limited application.

The second approach to leachate control is to regulate the amount
of water that can enter the landfill. As discussed earlier, proper
site selection, design, and construction can virtually eliminate infil-
tration into a landfill due to surface waters and ground water thereby
making the most vulnerable area of a properly engineered landfill its

upper surface.[23] Capping the upper surface with a water-impermeable (gas-permeable) material should provide an adequate means of preventing water infiltration.

Capping an entire landfill site is a rather new idea. Consequently the literature available on surface sealing or capping is extremely limited. Farb[5] mentioned surface capping in his EPA report and Tolman, et al.,[26] devoted a section to surface sealing in their report. The only documented case found in which an entire landfill was capped is that of New Castle County, Delaware.[5] The New Castle County landfill capped area covers approximately ten acres, using a coated polypropylene plastic (approximately 20 mils). The polypropylene was delivered in rolls ten feet by one thousand feet and installed by slowly unrolling it across the landfill. The seams were overlapped in shingle effect but not sealed.[5] As this has been a very recent undertaking there is nothing in the literature to date concerning the success of the New Castle venture.

There is little argument concerning the availability of materials and technology to install a water impermeable (gas permeable) cover over an entire solid waste disposal site. There are some unanswered questions concerning the integrity and durability of cover materials. However, since most materials recommended for use as landfill caps have been used widely in other applications (such as industrial and community holding/treatment lagoons) much that is known from these uses about their integrity and durability could be applied to their use as landfill caps.[8]

The major problem anticipated in the use of impermeable covers is a loss of cover integrity due to subsidence in the landfill.[8] Uneven subsidence could cause the cover material to tear or break apart at a

seam. Whether or not the cover material maintains its integrity during subsidence, low areas subject to ponding will be created. The repair of subsidence areas would require excavation and sealing to prevent water infiltration. However, excavation and repair would not be extremely difficult or expensive. In addition, the problem of subsidence should decrease rapidly as the landfill ages.

The greatest drawback to the use of water impermeable covers over solid waste disposal sites may be economic. At first glance this method might leave one with the impression that it is unnecessary and expensive. Nevertheless, the fact that some form of leachate control is necessary is becoming very apparent. News reports of problems associated with leachate pollution are becoming more prevalent. The Environmental Protection Agency is investigating more and more reports of contaminated land and groundwater resources due to leachate.[22] The tangible costs (corrective measures, avoidance, litigation, and the provision of an alternative water supply) associated with ten cases of water supply contamination due to leachate ranged from $7,000 to $2,000,000.[8] There can be no measure of the intangible costs (convenience, esthetics, social welfare, health, and psychic) to the individuals involved. A good description of the intangible costs suffered by individuals due to leachate contamination of well supplies is contained in EPA/530/SW-514, Leachate Damage Assessment, Case Study of the Fox Valley Solid Waste Disposal Site in Aurora, Illinois. One intangible cost of leachate contamination that cannot be measured is the loss of an aquifer.[36]

Of the means discussed previously under Prevention of Leachate Pollution, none could control the production of leachate. The early

basis of the practice of Sanitary Engineering was to protect the health of the public by breaking the disease-vector-host chain at its weakest link. To control water infiltration into the sanitary landfill and thus control leachate production seems the most logical engineering approach. It may also prove the most cost effective if initial costs are amortized over the expected life of the landfill. The installed cost of cover materials reproduced from Geswein[8] in Tables 1 and 2 are based upon the installed cost of liner materials. The comparison of costs is justified since the materials and recommended installation procedures are basically the same. Both require that the land be contoured prior to installation and that a proective earth cover (free of jagged rocks or other sharp objects) be installed. The actual installed cost of a given cover material may vary from the figures given in the tables due to changes in labor costs and rising costs of petroleum products. In addition, sanitary landfills constructed using the area or ramp method may require that a cap be installed over each lift thereby requiring several impermeable caps.[8]

A second cost analysis for cover materials from Tolman, et. al.,[23] in Table 3, is included for comparison. It should be noted that the following cost analysis is for remedial action. That is, it assumes that the landfill has been abandoned and must be re-entered to be sealed. As reported in the cost analysis the cost for installing a clay cap is provided. A clay cap is not considered an impermeable cover, but rather depends upon low permeability and the water balance method to reduce infiltration. However, clay caps are widely used in the United States, and their cost was included in order to provide a comparison to other materials.

TABLE 1

COST FOR VARIOUS SANITARY LANDFILL
LINER MATERIALS*(8)

Material	Installed Cost[+] ($/sq.ft.)
Polyethylene (10 – 20[±] mils[ss])	0.90 – 1.44
Polyvinyl chloride (10 – 30[±] mils)	1.17 – 2.16
Butyl rubber (31.3 – 62.5[±] mils)	3.25 – 4.00
Hypalon (20 – 45[±] mils)	2.88 – 3.06
Ethylene propylene diene monomer (31.3 – 62.5[±] mils)	2.43 – 3.42
Chlorinated polyethylene (20 – 30[+] mils)	2.43 – 3.24
Paving asphalt with sealer coat (2 inches)	1.20 – 1.70
Paving asphalt with sealer coat (4 inches)	2.35 – 3.25
Hot sprayed asphalt (1 gallon/yd^2)	1.50 – 2.00 (includes earth cover)
Asphalt sprayed on polypropylene fabric (100 mils)	1.26 – 1.87
Soil-bentonite (9.1 lbs/yd^2)	0.72
Soil-bentonite (18.1 lbs/yd^2)	1.17
Soil-cement with sealer coat (6 inches)	1.25

Source: Haxo, H.E. Jr., Evaluation of liner materials. U.S. EPA Research Contract 68-03-0230. October 1973.

Cost does not include construction of subgrade nor the cost of earth cover. These can range from $0.10 to $0.50/yd^2/ft of depth.

Material costs are the same for this range of thickness.

One mil = 0.001 inch.

TABLE 2

COST OF TAILINGS POND LINERS*(8)

Liner Material	Installed cost$^\pm$ ($/sq.yd.)
Bentonite	
18 lb/sq yd	1.26
Asphalt	
Asphalt membrane	1.26
Asphalt concrete	1.80
Rubber	
Butyl	
1/16"	3.78
3/64"	3.24
1/32"	2.70
Ethylene propylene diene monomer	
1/16"	3.69
3/64"	3.15
1/32"	2.61
Synthetic Membrane	
Polyvinylchloride	
10 mils	1.17 (includes
20 mils	1.62 earth
30 mils	1.98 cover)
Chlorinated polyethylene	
mils	2.34
mils	3.06
Hypalon	
mils	2.34
mils	3.06

Source: Clark, D.A. and J.E. Moyer. An evaluation of tailings ponds liners. Environmental Protection Technology series EPA-660/2-74-065. Washington, U.S. Government Printing Office, June 1974. p. 22-23.

Includes material and labor. Cost of subgrade preparation and, except where noted, earth cover is not included.

TABLE 3

COST OF CONSTRUCTING VARIOUS SURFACE SEALS[22]

Material	Installed Cost* ($/sq.yd.) +
Clay	
6-in	2.89 - 5.29
18-in	3.73 - 6.79
Bituminous concrete	
1.5-in	3.98 - 7.04
5-in	5.98 - 9.04
Fly-ash	
12-in	2.81 - 5.11
24-in	3.71 - 6.91
Soil-cement	
5-in	4.33 - 6.64
Lime-stabilized soil	
5-in	4.33 - 6.64
PVC membrane	
30-mil	8.03 -11.89

*Cost include: 18-in soil cover over surface seal material.
excavation of common borrow material for contouring
to bring surface to desired configuration.
excavation of the solid wastes during grading operations.
earthmoving operations, grading and compacting
materials, equipment and procedures for constructing
each seal, and a contingency factor of $0.02 per sq.
yd.

+To convert from $/sq.yd. to $/sq.m. multiply by 1.2

An important consideration in the construction of capped landfills should be gas venting. Some type of opening such as a gravel trench with a mushroom cap vent or gas venting wells must be installed in sealed landfills in order to allow gases formed during decomposition of refuse to escape.[8,23] The gas generated will be a mixture of methane and carbon dioxide (the exact percentage of each changing with time) and can be collected for sale.

An actual cost analysis of installing an impermeable cover versus conventional construction of a solid waste disposal site could not be made. However, it is believed that in the future, installation of an impermeable cover will be cost effective. It is not envisioned that the regulations and controls concerning solid waste disposal will be relaxed in the future; to the contrary, public awareness and concern over leachate pollution should result in a tightening of regulations and controls. Past experience in air and water pollution control indicates that the public will not accept the argument that the natural environment will "purify" leachate. Therefore, since virtually all solid waste disposal sites in the United States have the potential to produce leachate, they will most probably have to be capped or lined.

The cost of installation of an impermeable cover was found to be very similar to that for installation of a liner. However, after installation of a cover, no further maintenance should be required. The installation of a liner, on the other hand, would imply the installation of a leachate collection and treatment system with its associated cost. The cost of leachate treatment could not be found, probably

due to the fact that no one treatment system can be applied to leachate treatment. In addition, it may be necessary to install monitoring wells around the lined landfill to monitor groundwater.

Changing Composition of Municipal Refuse

The inclusion of a section concerning the changing composition of solid wastes in a chapter that deals with the disposal of solid wastes and leachate production/control may appear misplaced. However, the composition of solid wastes is considered a very integral part of the leachate control problem. As discussed in the previous section, long-term (stage 3) leachate production can be prevented by the use of water impermeable covers or caps. Therefore, stages 1 and 2 leachate production become very important since, as discussed earlier, their production is directly related to the composition of the solid wastes deposited.

The available data concerning the composition of solid waste indicates a strong interest in the early 1900's which gradually died off by 1940. Hering and Greeley[1] experienced little trouble obtaining data on the composition of municipal refuse for their book. They reproduced tables from studies performed in cities across the United States. An example of the data collected from one such study conducted in Chicago is reproduced in Table 4.[1]

The wards served by the Chicago Bureau of Streets were divided into seven groups based on the social economic status of the residents, as well as the type of buildings and their use. Group A was composed of businesses and manufacturing areas. The other groups were comprised

TABLE 4

RESULTS OF ANALYSIS OF REFUSE IN CHICAGO, FROM JUNE 17, TO SEPTEMBER 16, 1914[1]

Group	# of Loads	Ashes (lbs)	Glassware (lbs)	Metals (lbs)	Paper (lbs)	Rags (lbs)	Rubber (lbs)	Leather (lbs)	Wood (lbs)	Brick (lbs)	Yard Cleanings (lbs)	Garbage (lbs)	Totals (lbs)
A	1	2,679	147	49	373	49	0	65	64	16	0	308	3,750
B	7	11,082	1,036	1,036	2,215	199	20	64	331	359	5,646	360	22,442
C	12	22,290	1,724	2,284	3,642	507	0	165	690	512	5,811	704	38,329
D	12	22,058	1,778	2,811	3,228	490	0	217	570	566	5,077	835	37,630
E	14	21,119	1,618	2,745	4,219	658	4	323	1,048	744	9,580	2,087	44,145
F	7	11,439	891	1,130	2,134	303	13	123	694	428	3,402	1,168	21,725
Total	53	90,667	7,194	10,149	15,811	2,206	37	957	3,397	2,625	29,516	5,462	168,021
Average per load		1,711	136	152	196	42	0.7	18	47	50	427	103	2,882.7
Percentage per load		59.4	4.7	5.3	6.8	1.5	--	0.6	1.6	1.7	14.8	3.6	100.0

of residential areas divided primarily by social-economic differences.
It should be noted that Table 4 shows the composition of solid
wastes for the summer months, June to September. This is important
because it affects the percentage of ashes and garbage found in the
solid wastes. Ashes were low due to lack of heating requirements and
garbage (decomposable organics) was slightly increased due to the avail-
ability of fresh vegetables and fruits.

Data concerning the composition of solid waste from the period of
1918 to 1968 were difficult to obtain. The main reason for the difficulty
appears to be a general lack of interest. The Sanitary Engineering
Research Committee, Solid Waste Engineering Section 1959 report demon-
strates the level of research conducted in solid wastes in the United
States.[37] The findings of the Committee's survey of schools offering
sanitary engineering programs showed that only three reported having
done research on solid wastes.

Despite a lack of interest by most, some work in solid wastes was
performed. Table 5 gives data on refuse composition for the City of
New York in 1939.[38] The variances in the percentage of ash and garbage
are very apparent in the New York City study. In the 1914 Chicago study,
ashes accounted for 53.65 percent of the refuse. Twenty-five years
later the New York City study showed refuse containing only 17.78 percent
ash during the summer months. Based upon comparisons with similar
studies of the same time period, it appears that the figures given
for garbage in the Chicago study are low. Therefore, no comparison
of garbage was made. One very interesting item noted was the substantial

TABLE 5

MONTHLY DISTRIBUTION BY WEIGHT OF ORGANIC AND INORGANIC
REFUSE DISPOSED OF IN NEW YORK CITY, 1939[37]

Percent by Weight

	Organic					Inorganic			
Month	Garbage	Misc.	Paper	Wood	Total	Metal	Glass	Ashes	Total
January	5.7	1.0	12.4	0.3	19.4	4.3	4.0	72.3	80.6
February	9.0	1.7	12.6	0.7	24.0	6.6	4.9	64.5	76.0
March	9.7	2.1	20.6	0.3	32.7	7.4	7.3	52.6	67.3
April	18.1	2.8	21.6	2.0	44.5	7.4	6.9	41.2	55.5
May	26.7	3.3	23.0	3.1	56.1	7.1	6.8	30.0	43.9
June	35.1	3.8	24.3	4.6	67.8	6.4	6.8	19.0	32.2
July	43.8	4.1	25.5	5.9	79.3	6.6	6.3	7.8	20.7
August	23.1	7.4	37.6	3.8	71.9	11.6	5.1	11.4	28.1
September	12.6	5.6	26.7	4.9	49.8	8.2	9.1	32.9	50.2
October	10.1	3.8	31.0	2.6	47.5	8.9	4.0	39.6	52.5
November	6.6	1.9	18.0	2.1	28.6	3.8	2.9	64.7	71.4
December	3.5	0.8	9.0	0.8	14.1	3.1	1.9	80.9	85.9
Average	17.0	3.2	21.9	2.6	44.7	6.8	5.5	43.0	55.3

increase in the percentage of paper and paper products that occurred in the twenty-five years from 1914 to 1939.

The continuance of the above trend in paper and ash content in refuse is reproduced from Haxo[38] in Table 6. The data came from the City of Chicago and covers the time of 1956-1958. The percent of paper climbed from 9.36 percent in 1914 and 29.9 percent in 1939 to 56.5 percent in 1956-1958. In the meantime, the composition of ash in refuse declined from a yearly average of 43.0 percent in 1939 to 18.7 percent in 1956-1958.

The percentages of paper and garbage in solid wastes appeared to have stabilized in the late 1950's. The 1968 Bureau of Solid Waste Management study of the composition of solid waste, Table 7, shows a 51.2 and 19.3 percentage, respectively.[39] The percentage of ash in solid wastes during this time was not given. However, based upon modern methods of heating and cooking, the ash composition of solid wastes is probably no longer significant.[37]

The studies performed by the Office of Solid Waste, Resource Recovery Division, Table 8, also show a general stabilization in the generation of paper and garbage wastes.[40]

The apparent reduction in the percent composition of paper shown by the data is due to government estimates of recycling. As an example, the gross consumer discards of paper in 1975 was 51.6 percent; the net discards by government estimate was placed at 37.1 percent.[39]

The reduction of the percentage of composition of paper, metals, and glass due to recycling efforts is significant. The moisture content of common constituents of municipal solid waste are reproduced in

TABLE 6

PHYSICAL ANALYSIS OF REFUSE BY WEIGHT
CHICAGO, 1956-1958[37]

		Percent by Weight					
Date	Number of Samples*	Paper	Grass	Garbage	Metal	Glass	Ashes
3/56	10	50.1	...+	6.4		18.5	25.0
4/56	8	64.0	...	7.4		13.9	14.7
5/56	9	57.3	11.9	5.6		14.0	11.2
6/56	6	60.7	6.5	2.5		13.6	16.7
10/56	6	56.0	4.5	3.5		11.9	24.1
2&3/57	4	49.2	...	6.1		17.5	27.2
4/57	1	53.3	19.7	3.2	9.3	5.9	8.6
9/57	2	42.0	23.0	3.6	7.4	5.4	18.6
11/57	1	59.3	3.7	2.3	5.2	6.5	23.0
2/58	1	57.6	...	5.7	11.6	9.3	15.8
/58	1	56.3	...	1.5	7.5	6.0	28.7
	1	70.4	...	2.6	8.0	− 6.9	12.1
		63.7	...	1.5	8.1	5.8	20.9
	1	54.7	34.4	0.8	6.2	3.5	0.4
		56.5	9.6	4.8		14.8	18.7

... of one truck load of refuse (approximately three
... ... this category not performed; grass included with paper.

TABLE 7

ESTIMATED ANNUAL AVERAGE NATIONAL REFUSE COMPOSITION
FOR 1968(38)

Component	Mean Weight (%)
Glass	9.9
Metal	
Paper	
Plastic	
Leather, Rubber	1.9
	5.9
	19.3
	100.0

TABLE 8

POST CONSUMER NET SOLID WASTE DISPOSED OF BY MATERIAL
(1971-1975)*(39)
AS GENERATED WET WEIGHT (%)

Materials	1971	1972	1973	1974	1975
Paper	39.6	40.8	41.0	40.4	37.1
Glass	12.1	12.2	12.3	12.0	13.3
Metal	11.9	11.6	11.5	12.1	12.2
Plastics	4.3	4.5	4.6	4.2	4.4
Rubber and Leather	3.3	3.3	3.3	3.8	3.3
Textiles	1.8	1.7	1.8	2.0	2.1
Wood	4.7	4.5	4.6	4.5	4.9
Food Wastes (Garbage)	22.2	21.3	20.8	21.0	22.8
Total	99.9	99.9	99.9	100.0	100.1

*Office of Solid Waste, Resource Recovery Division, and Franklin
Associates, Ltd. Revised February 1977.

Table 9.[41] Disregarding variances due to weather and unforeseen inci-
dents, it is obvious that by reducing the amount of paper products, metals,
and glass through recycling, the moisture content of the solid wastes
is going to increase. The increase in moisture content in turn will
favor stage-1 and-2 leachate production.

The Federal government through the Resource Conservation and Recovery
Act has indicated the direction that the composition of solid waste
will take. Those materials most easily recoverable and with the greatest
market value (paper products, metals, and glass) will be recycled in
greater and greater amounts. While recovery and recycle are laudable
goals, their implementation will increase the production of stage-1 and-2
leachate production. Although it is not possible to place a number
figure on the increase, it is apparent that good sanitary landfill
design must include controls for leachate production.

TABLE 9

TYPICAL DATA ON MOISTURE CONTENT OF
MUNICIPAL SOLID WASTE COMPONENTS[40]

	Moisture, percent	
Component	Range	Typical
Food wastes	50-80	70
Paper	4-10	6
Cardboard	4-8	5
Plastics	1-4	2
Textiles	6-15	10
Rubber	1-4	2
Leather	8-12	10
Garden trimmings	30-80	60
Wood	15-40	20
Glass	1-4	2
Tin cans	2-4	3
Nonferrous metals	2-4	2
Ferrous metals	2-6	3
Dirt, ashes, brick, etc.	6-12	8
Municipal solid wastes	15-40	20

CHAPTER III

EXPERIMENTAL PROCEDURES

Obtaining samples of leachate for laboratory analysis proved more difficult than anticipated. It was learned that even in poorly operated landfills it is difficult to locate the leachate generated. A satisfactory source was eventually found that provided a good source of young (approximately two-year old) leachate.

This chapter discusses the leachate sources, the laboratory apparatus used, and the laboratory tests performed. Distilled water blanks to which activated carbon was added were included in all the adsorption tests described in this chapter in order to correct for any organic compounds that might have dissolved from the carbon. The granular activated carbon used for all testing was Calgon Filtrasorb 400.

Collection of Leachate Samples

Leachate samples were obtained from a closed city landfill (see Figure B-1, Appendix B). The landfill site was closed to dumping by the city, but had not been approved for abandonment by the Texas Department of Health.[24] The major obstacles to abandonment were the lack of a final cover over the landfill site and the existence of numerous leachate springs within the site.

Three leachate springs within the closed city landfill were used to provide samples for the study. Springs 1 and 2 are located within six feet of each other and are approximately one-hundred and fifty yards into the site beyond the access gate and fifty yards to the southwest

of the access road (see Figure B-1, Appendix B). The flow from
these springs was a reddish-brown color and possessed a mild odor. A
total of four samples of four liters each (one from each spring during
two separate visits), were collected before springs 1 and 2 ceased
production due to lack of rain.

Leachate from spring 3 was located approximately four-hundred yards
into the site past the access gate and twenty yards north of the point
where the access road ended (see Figure B-1, Appendix B). Two
sampling points were used to collect samples from spring 3. The first
sampling point was approximately four yards south of spring 3 at the
first place the leachate pooled. The second sampling point was approxi-
mately eight yards south of spring 3 where the leachate flow had diluted
into a large pond of rainwater. The flow from spring 3 was black and
possessed a strong odor.

All samples were collected by dipping a cut-off, one-gallon plas-
tic container into pooled leachate and transferring the liquid to
a five-gallon polyethylene pail. The pail was then sealed for trans-
port to the Water Laboratory, Civil Engineering Building, Texas A&M
University. Transportation required approximately one and one-half
hours. At the laboratory the samples were refrigerated until use.

Carbon Adsorption Testing

Two types of carbon adsorption tests, rate and equilibrium, were
conducted on the leachate. Both tests were conducted using 500-ml
Erlenmeyer flasks and the Controlled Environment Incubator Shaker manu-
factured by New Brunswick Scientific. The granular carbon used in the

tests was first washed with distilled water to remove any trash materials, oven dried at 104°C, and then pulverized prior to use. Granular carbon used in the first equilibrium test was pulverized by hand using a mortar and pestle. No care was taken to determine the size of the pulverized carbon particles. Pulverized carbon used in subsequent tests, rate and equilibrium, was crushed mechanically using a Hamilton Beach Cookbook Blender, and then passed through a U.S. Standard Sieve Series No. 200, prior to use.

The rate test was performed by adding 0.5 gm of pulverized carbon to 100 ml of leachate in a 500-ml flask. Five flasks were prepared, then placed in the shaker at room temperature and agitated at 160 rpm. Flasks were withdrawn at different times over 2 four-hour periods. The leachate/carbon mixture was immediately removed from the flask and passed through a membrane filter to separate the carbon from the sample. Following the filtering operation, the samples were stored at 4°C until chemical oxygen demand (COD) analyses could be made.

The equilibrium tests were performed by adding differing measured amounts of pulverized carbon to each of at least nine 100-ml samples of leachate contained in 500-ml flasks. There was some concern that complete mixing would not occur since the flasks were not baffled. Therefore, three duplicate samples per test were prepared. The flasks were then placed in the shaker at room temperature and agitated at 160 rpm for a minimum of two hours. When the agitation time was complete, the samples were withdrawn from the flasks, centrifuged at 7500 rpm for fifteen minutes using a Sorvall Super Speed Automatic Refrigerated Centrifuge, and then passed through a membrane filter to remove

the carbon. Following the filtering operation, the samples were stored at 4°C until COD analyses could be made.

Another equilibrium test was performed to determine the adsorbable fraction of the leachate. A measured amount of granular carbon was added to 150 ml of leachate samples in two 500-ml flasks. The flasks were then placed in the shaker at room temperature and agitated at 160 rpm for two hours. When the agitation time was complete, the samples were withdrawn and then passed through a glass fiber filter to remove the carbon. A sample was then extracted for analysis from each of the filtered leachate samples. The remaining filtered leachate samples were placed in 500-ml flasks with measured amounts of carbon. The flasks were placed in the shaker and the above procedure repeated through seven repetitions until the filtered leachate sample volume was exhausted.

Carbon Column Tests

One of the objectives of the study was to determine if carbon adsorption would provide a feasible means of control for initial (stage-1 and -2) leachate production. The control technique would be to line the landfill with tivated carbon prior to depositing the solid wastes. Since the environment at the bottom of a landfill where adsorption would are place would become anaerobic, it was decided to conduct the carbon column tests under anaerobic conditions. To achieve anaerobic conditions the carbon column apparatus was constructed as a sealed system with a nitrogen atmosphere.

The carbon column apparatus, shown in Figure 1, consisted of a nitrogen source, three elevated five-gallon sample containers, three plexiglas tubes, three 250-ml Erlenmeyer flasks, and three five-gallon
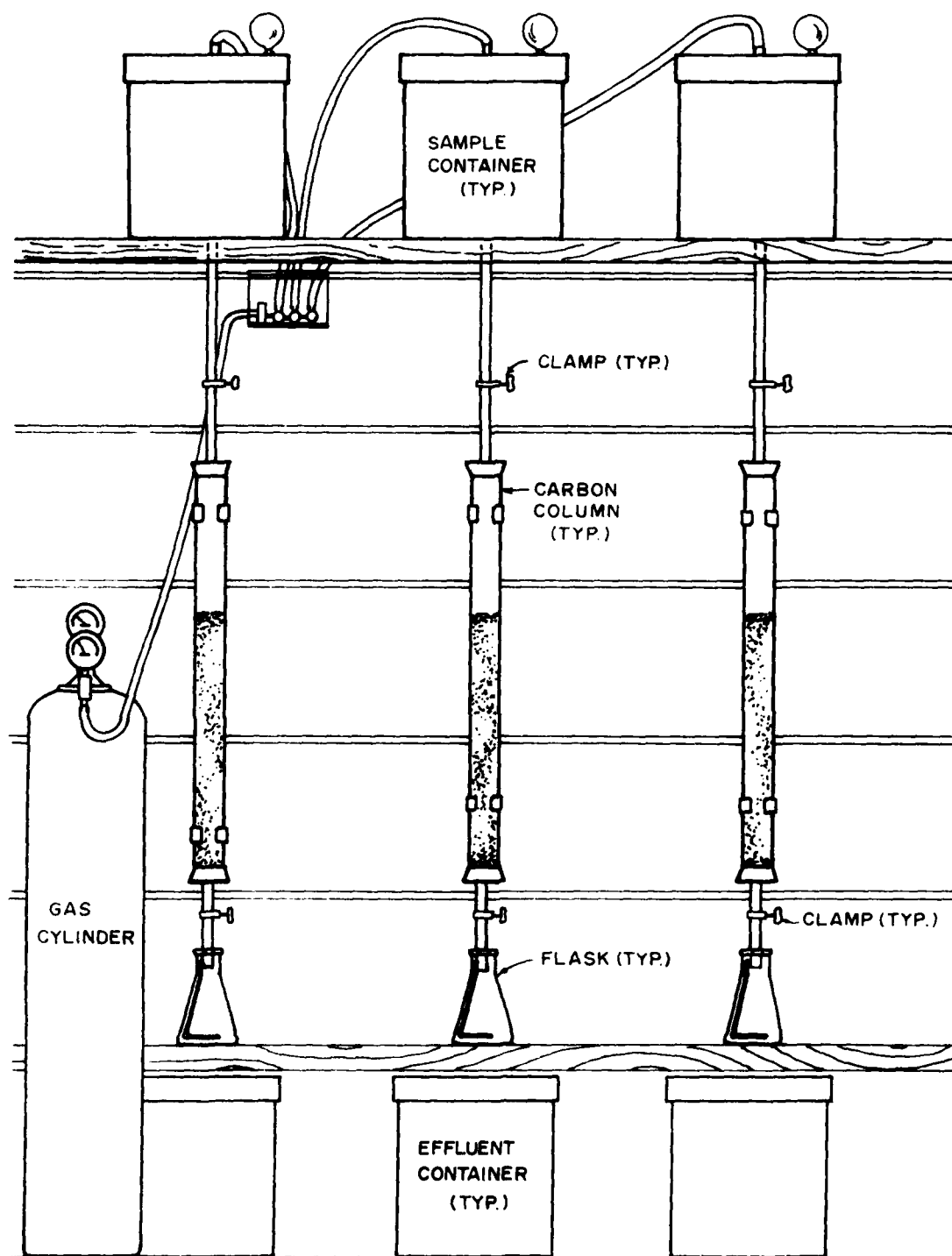
FIGURE I.   CARBON   COLUMN   APPARATUS.

effluent containers. The apparatus was connected together through flex-
ible and non-flexible plexiglas tubing. Flow in each column was con-
trolled by two screw-type flexible tubing clamps, one located between
the sample container and the carbon column and the other between the
carbon column and the flask. The leachate sample was introduced into
the five-gallon plastic sample container at the top of the apparatus.
The sample container was constructed with three openings, a bottom
drain, a top gas inlet, and a top gas outlet. With the bottom drain
clamped, the first leachate sample was poured in through the open lid.
After the first sample was in place the lid was sealed, requiring sub-
sequent samples to be pumped in through the bottom drain.

With the leachate sample in place, nitrogen gas was introduced
under pressure through the gas inlet tube in order to purge the air
above the sample. After three minutes of purging the pressure was
reduced and the gas outlet tube was sealed by placing a small round
balloon over it. The ballon sealed the gas outlet tube and acted as
a simple pressure indicator.

The plexiglas column tubes were secured in a vertical position
below the sample containers by clamps. Modified rubber stoppers were
inserted in the bottom of the tubes. The stoppers had 3/16-inch plexi-
glas tubes inserted in their centers and pieces of nylon stocking
covering the inner faces. The purpose of the nylon was to prevent
carbon from leaving the column with the sample.

Granular carbon used in the carbon columns was washed, oven dried,
and weighed in a 500-ml beaker prior to loading in the column. The
loading procedure consisted of adding leachate to the carbon and manually
stirring to dispel the air bubbles that occur when dry carbon comes in

contact with water. A one-half inch layer of 5-millimeter (mm) diameter glass beads was added to facilitate flow. The beads were followed by approximately 100 ml of leachate. The wetted carbon was then gradually fed in from the top of the column. Vigorous tapping on the sides of the column accompanied the carbon feed in order to enhance compaction and remove any air bubbles entrained in the pores of the carbon.

After the carbon was in place, 5-mm diameter glass beads were added to a depth of one and one-half inches in order to distribute the flow evenly. The glass beads were followed by a three-inch layer of loosely packed Pyrex brand wool filtering fiber. The filtering fiber was included because the leachate feed was in the raw state (unfiltered) and could contain some large materials that would interfere with the flow in the carbon column. With the fiber in place the remaining air space in the tube was purged with nitrogen and the top stopper (connecting the column to the sample container) was put in place. The column was left sealed overnight prior to start-up. The procedure used throughout the carbon column tests was to begin flow in the morning and stop it each evening giving a flow time of eight to ten hours per day. So long as a steady state did not exist in the column, starting and stopping the column did not affect the results.[42]

The column operation was conducted by allowing the leachate to flow by gravity feed through the column. Flow rates were monitored by observing the time required to fill the flasks beneath the columns to specific marks. Clamps were used to control the flow accordingly.

Samples for analysis were obtained at prescribed intervals by removing the stoppers from the flasks located below the columns and

inserting test tubes in the line of column effluent flows. The samples were then stored at 4° C until COD analysis could be made.

The flow from the flasks was by siphon to the effluent containers. The volume of effluent collected each day was carefully measured, and the flow rate through the columns was assumed constant. Therefore, by dividing the volume collected plus the sample volume extracted by the time of column operation, the daily flow rates for the columns could be determined.

COD Analysis

Chemical oxygen demand determinations were made using the procedures set forth in the 14th Edition of Standard Methods for the Examination of Water and Wastewater.[43] The sample size chosen for analysis was 20 ml, which allowed full sample strength COD values of up to 1000 mg/l. Since the COD of the raw leachate was approximately 7000 mg/l, most samples required diluting. Great care was taken in preparing the dilution, because small errors in dilutions would result in large errors in COD values. Generally, dilutions of one to four were made by pipeting five milliliters of sample directly into a 250-ml flask and diluting to 20 ml with distilled water. Dilutions greater than one to four were made by pipeting five milliliters of sample into a 125-ml Erlenmeyer flask, diluting to the desired strength, and then pipeting twenty milliliters into a COD flask. Any COD value that appeared questionable for any reason was repeated.

BOD Analysis

Biochemical oxygen demand (BOD) determinations were made using the procedures set forth in the 14th Edition of <u>Standard Methods for the Examination of Water and Wastewater.</u>[43] Since leachate is such a unique and strong pollutant it was decided to develop a seed for the BOD determinations. Consequently, two batch reactors were started up early in the laboratory procedures. The seed for each of the reactors consisted of 1.5 liters of supernatant from the re-aeration tank of the College Station sewage treatment plant, soil from the leachate collection site, and 200 ml of water plus scrapings from a mildly polluted pond near the leachate collection site. The feed stock for the reactors came from the diluted leachate samples collected. The mixed liquor suspended solids (MLSS) and the food to microbe ratio (F/M) of both reactors was monitored during the entire laboratory procedures.

To check for acclimation, Kjeldahl nitrogen determinations were performed on both reactors. Because of inconclusive results, the Kjeldahl tests were followed by COD determinations to determine acclimation.

CHAPTER IV

EXPERIMENTAL RESULTS

Chapter IV gives the results of the experimental procedures des-
cribed in Chapter III and how the results relate to the age of the
landfill from which the samples were obtained. Discussion of the
results of equilibrium and column tests and their relationship to the
treatability of leachate by activated carbon adsorption is reserved for
Chapter V.

The leachate samples used in the experimental procedures came from
ns within the city of landfill and are numbered one through
10 shows the relationship between the sample number and

measure the strength of each

from a sample site collection.

COD determinations given in Table 10

with the relationships between COD values and age of
found in the literature. Based upon the COD value reported
sample site number 3, Poriland's[?] study of
place the age of the closed fill at approximately twenty
years. Chain and DeWalle[??] would place the age of the closed
landfill sample site 3 at less than five years, and the age of the
for sample sites 1 and 2 at over ten years.

TABLE 10

RESULTS OF INITIAL COD DETERMINATIONS

Sample Number	Sample Source	Collection Sequence	Age of Landfill Source Area+ (yrs)	COD (mg/1)
1a	Leachate Spring 1	first	15	483
1b	Leachate Spring 1	second	15	292
2a	Leachate Spring 2	first	15	698
2b	Leachate Spring 2	second	15	216
3a	Leachate Spring 3	first	2	17,741
3b	Leachate Spring 3	second	2	17,480
3c	Leachate Spring 3	third	2	17,100
4a	Rainwater plus Leachate Spring 3	first	2	4,646

+Age supplied by Price, W.C., Geotechnical Geologist, Division of Solid Waste Management, Texas Department of Health.

Carbon Adsorption Testing

A rate adsorption test using leachate 3a was performed to insure that sufficient contact time was allowed during subsequent equilibrium testing. Data results for the rate adsorption test are listed in Table A-1 of Appendix A and Figure 2 is a plot of the percent adsorbate remaining in the sample versus contact time. Reynolds states that equilibrium should occur within about forty minutes.[44] The curve of Figure 2 appears to reach equilibrium within that time. The minimum time for any of the equilibrium tests was two hours, allowing ample time to assure that equilibrium was reached.

The equilibrium tests were conducted using pulverized carbon. Differing amounts of carbon were added to flasks containing one-hundred milliliters of leachate. One-hundred milliliters of leachate was assumed to weigh one-hundred grams. That assumption was checked by carefully measuring fifty milliliters of leachate into a one-hundred milliliter beaker and weighing using an analytical balance.

The data results of the equilibrium tests are disclosed in Tables A-2, A-3, and A-4 of Appendix A. Figures 3, 4, and 5 are plots of the equilibrium ratio, x/m, versus their corresponding equilibrium concentrations.

The empirical Freundlich equation was selected to mathematically represent the adsorption isotherm. The basic form of the equation is,

$$x/m = ck^{1/n}$$

Equation 1[44]
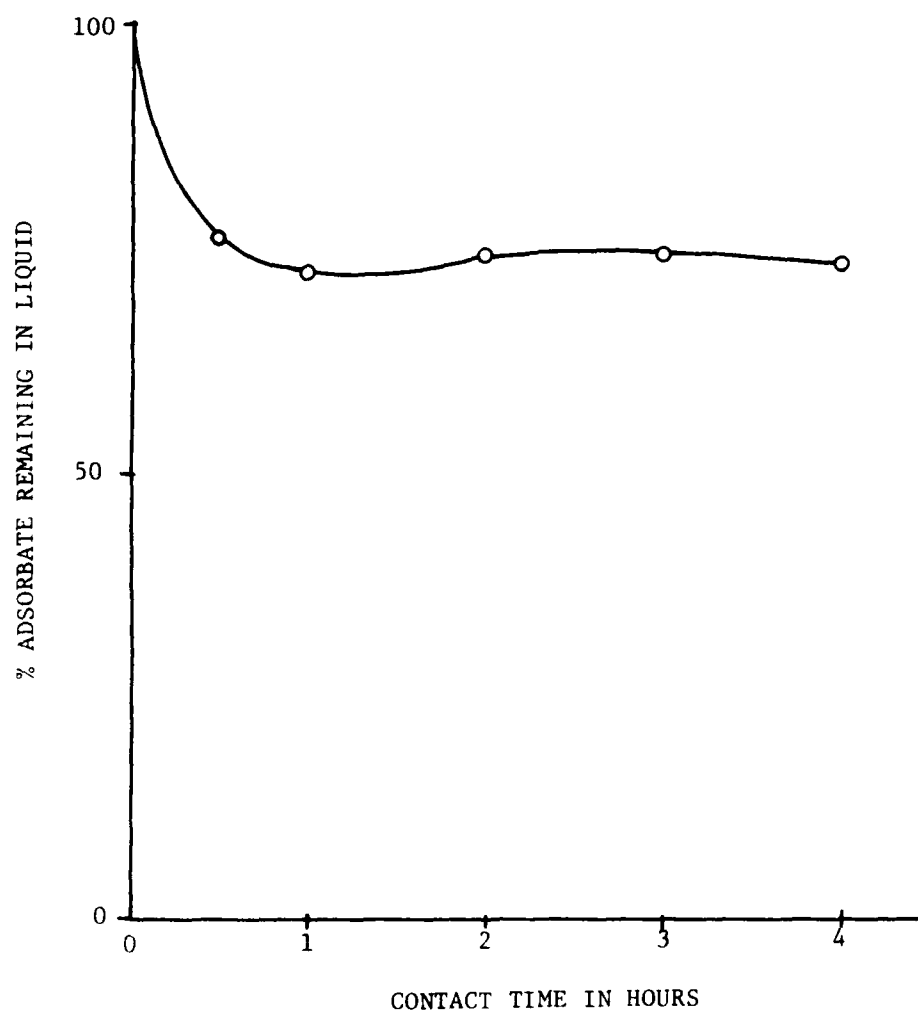
FIGURE 2. Rate of Adsorbance of Leachate Sample 3a.

where

    x = amount of adsorbate adsorbed

    m = weight of carbon

  x/m = concentration in the adsorbed phase, that is, the amount of
          adsorbate adsorbed per unit weight of carbon

    c = equilibrium concentration of adsorbate in solution
        after adsorption

k and n are constants.

By taking the logarithm of both sides of the above equation,
the form

$$\log x/m = \log k + 1/n \log c$$
<div align="right">Equation 2[44]</div>

is obtained. The logarithmetic form of the Fre·ndlich equation is the
equation of a straight line whose slope is $1/n$ and whose intercept
is k at c = 1. The value of n does not change regardless of the
units used for the equilibrium concentration. The larger the n value
the more feasible the use of carbon adsorption, with an n value less
than one generally considered economically unfeasible.[42]

The n values determined from Figures 3, 4, and 5,
were 0.32, 0.30, and 0.47 respectively. These n values indicate that
carbon adsorption of raw leachate was not economically feasible. However,
the use of carbon for adsorption of leachate could not be ruled out
since economic considerations are not always the deciding factor in
engineering design.[42]
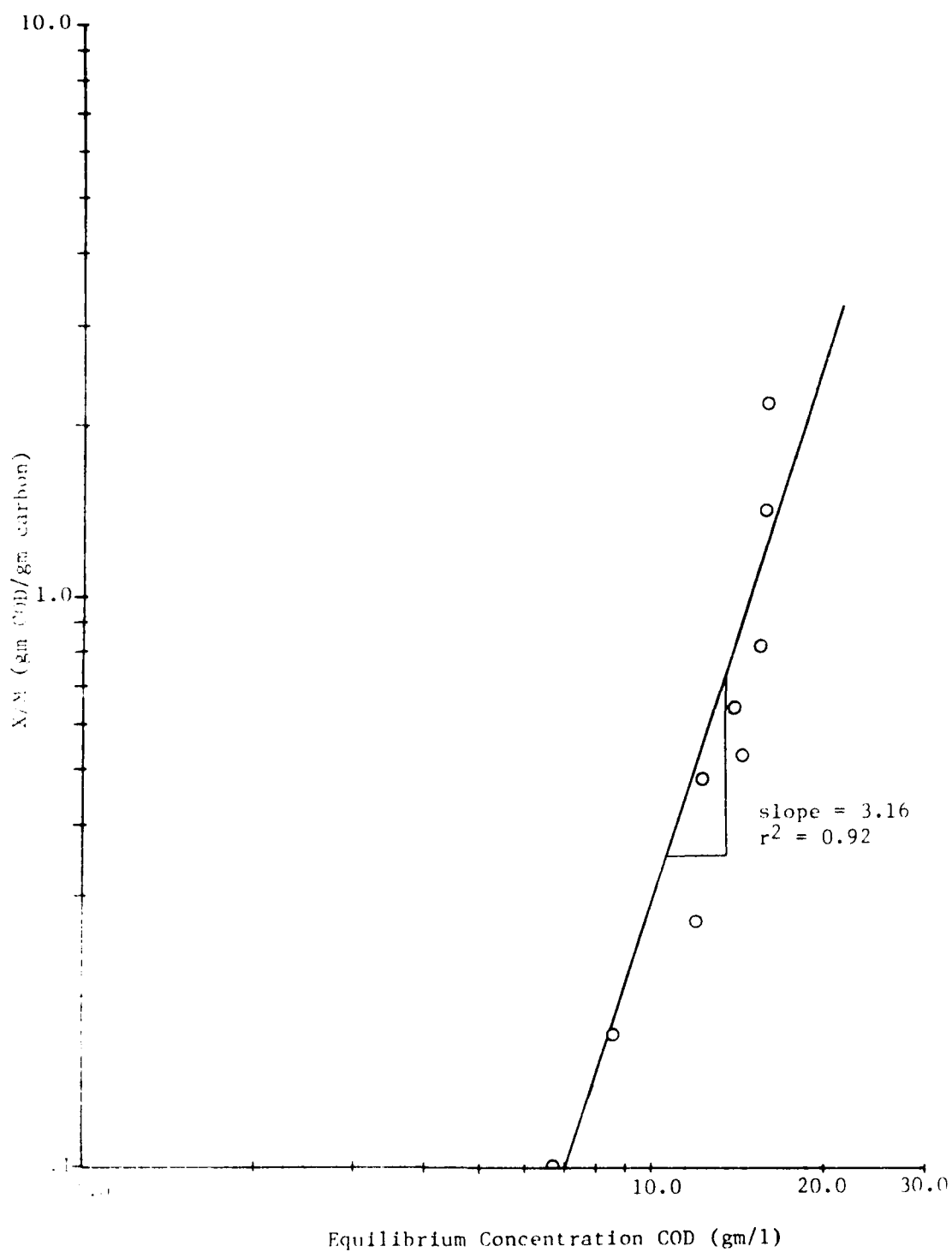
FIGURE 3.   First Equilibrium Isotherm Test, Leachate 3a
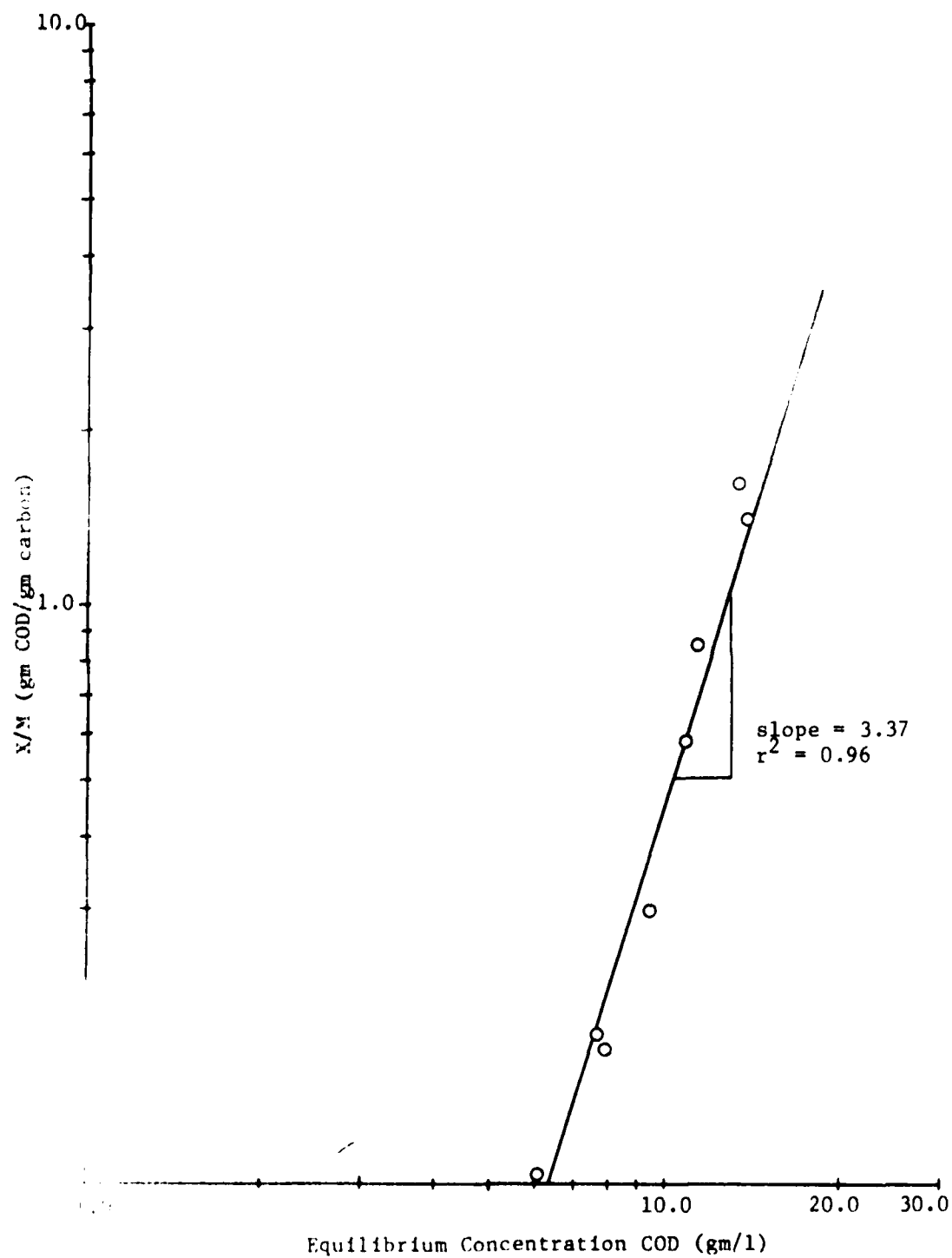
FIGURE 4.   Second Equilibrium Isotherm Test, Leachate 3a
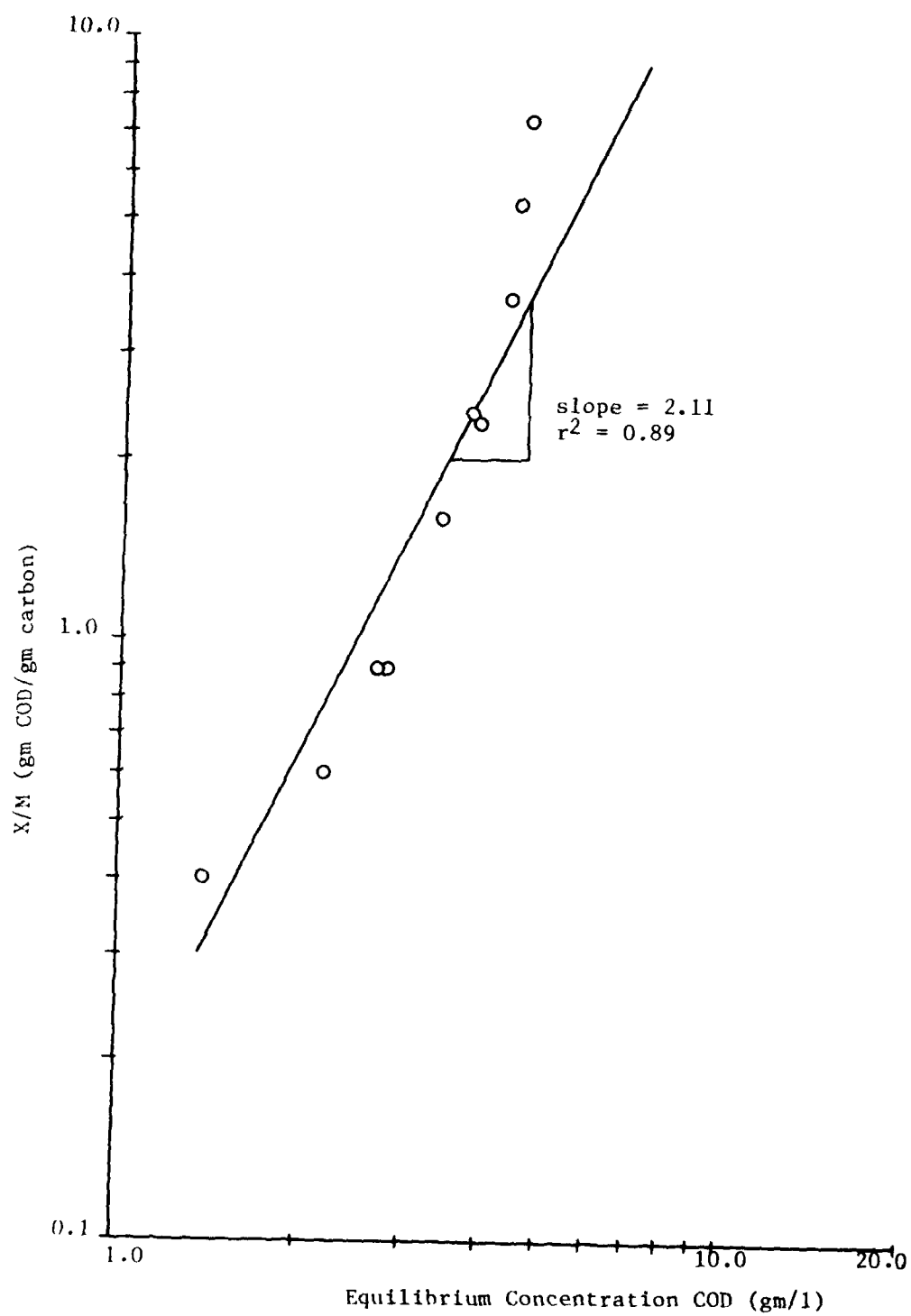
FIGURE 5.   Third Equilibrium Isotherm Test, Leachate 4a

Carbon Column Tests

An initial column of 1-inch interior diameter and a carbon column
height of 32 inches was utilized. Operational data included: leachate
sample = 3a, empty bed volume of column = 411 ml., C_o = 17,740 mg
COD/1, liquid flow rate varied from 175 to 472 cm/hr, (.14 to .38
gal/min/ft^2), retention time varied from 2.35 hr to .87 hr, and allowable
breakthrough concentration C_a = 5 mg/1. Table A-5 of Appendix A sum-
marizes the column operational data. The shape of the initial data
plots, shown in Figure 6, was not anticipated; an initial concentration
of approximately 2000 mg COD/1 appeared immediately and was followed
by apparent rapid saturation of the carbon.

The behavior of column 3a was attributed to the
possibility of a large nonadsorbable fraction present in the leachate
or to channeling. In order to obtain further data for evaluation it
was decided to pass the effluent from the first column, designated
leachate 3a - Sub 1, through a second carbon column. In addition, a
column with a larger diameter (1-3/8 inches) was chosen to better reduce
the possibility of channeling. Operational data for column 3a-Sub 1
included: leachate sample = 3a-Sub 1, mass of carbon in column =
200 gms, C_o = 8892 mg/1 COD, empty bed volume = 413.7 ml, liquid flow
rate = 200 to 310 cm/hr, (.82 to .13 gal/min/ft^2), retention time =
1.33 to 2.07 hr, and allowable breakthrough concentration C_a = 5 mg/1.
Table A-6 of Appendix I summarizes the column operational data.
The shape of the second breakthrough curve, shown in Figure 7, has
a more S-shape form, but it too demonstrated a near immediate concen-
tration of approximately 2000 mg COD/1 in the effluent.
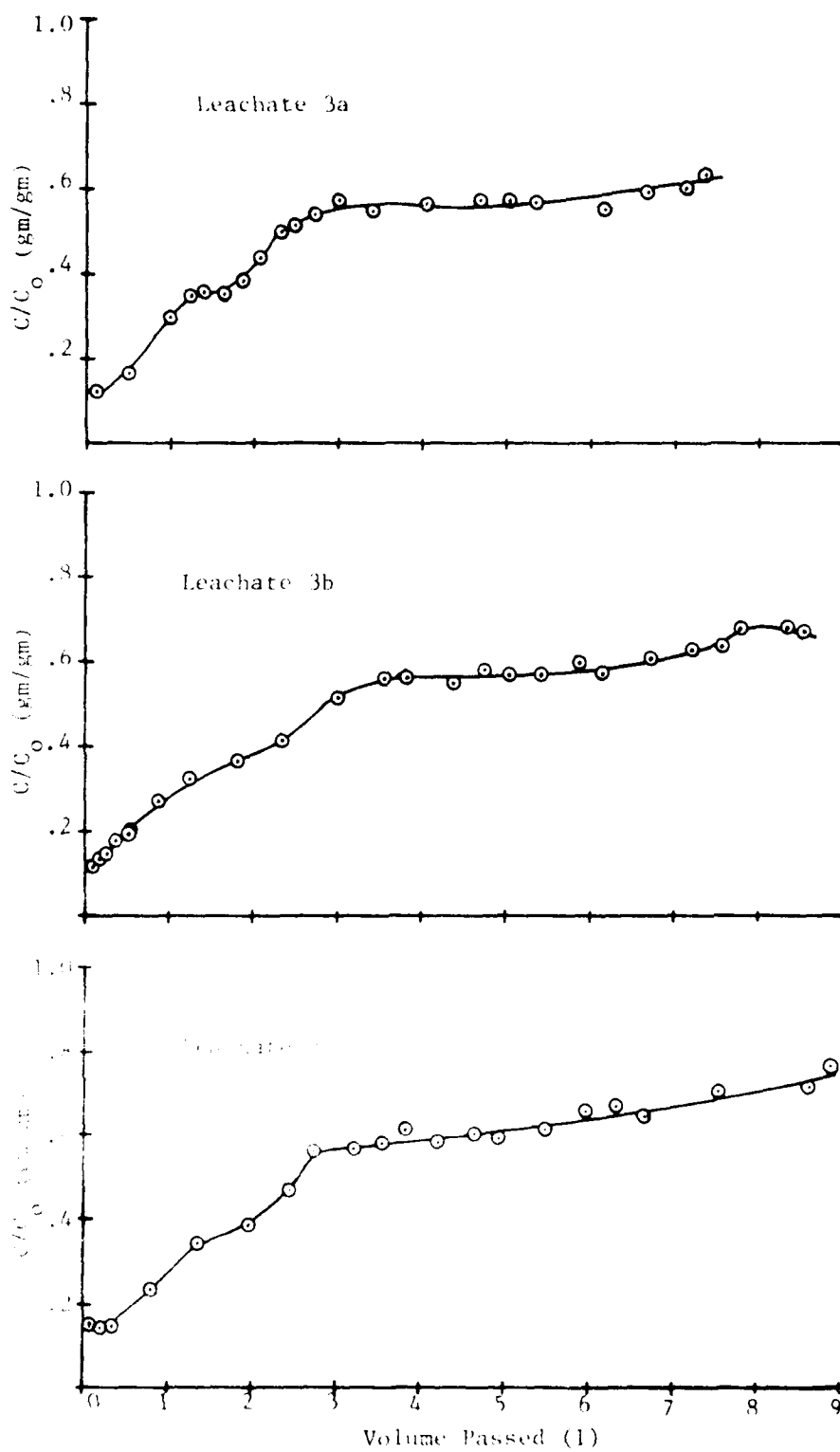
FIGURE 6. Data Plot Curves for First Column Tests
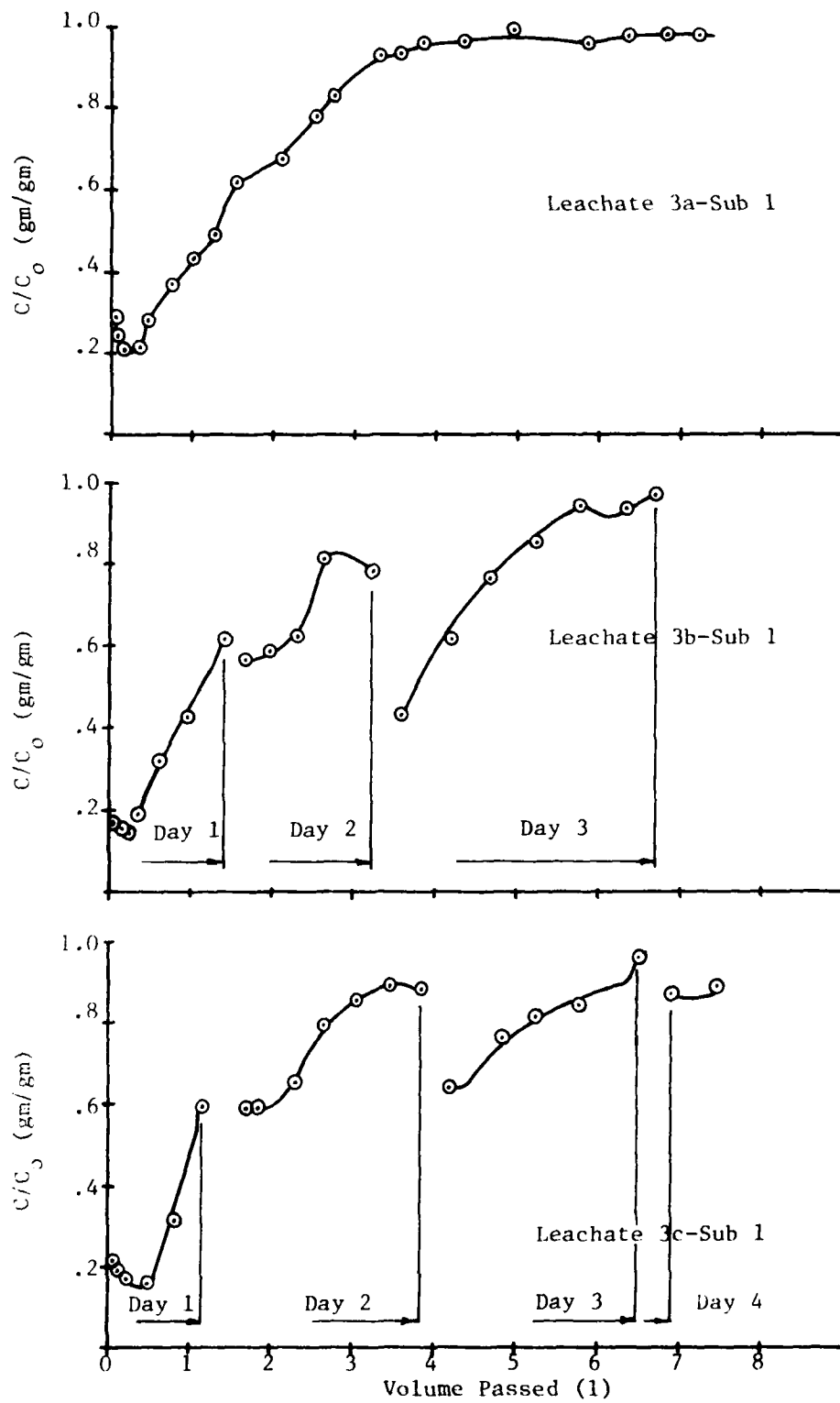
FIGURE 7. Data Plot Curves for Second Column Tests

The S shape plot of the data obtained from column 3a-Sub 1

was encouraging, and two more columns of 1-3/8 inch diameter containing

200-gms carbon were set up to test leachate samples 3b and 3c. The

operational data for column 3b were Co = 17480 mg/1 COD, carbon

height = 17-1/8 inch, empty bed volume = 416.7 ml, liquid flow rate =

231 to 369 cm/hr, (.099 to .158 gal/min/ft^2), and retention time =

1.13 to 1.80 hr. In light of the results from the previous carbon

column tests the idea of establishing an allowable breakthrough concen-

tration was abandoned. Table A-7 of Appendix II-A summarizes the column

operational data. The shape of the data plot for column 3b shown

in Figure 6 was similar to the shape of the date plot curve for

column 3a.

The operational data for column 3c were Co = 17100 mg/1 COD,

carbon height = 17-1/8 inch, empty bed volume = 416.7 ml, liquid flow

rate = 96 to 350 cm/hr, (.004 to .150 gal/min/ft^2), and retention time =

1.19 to 4.34 hrs. Table A-8 of Appendix A summarizes the column oper-

ational data.

The rather large variation in the reported flows was due to plug-

ging of the column. The flows recorded for the first ten liters of

sample ranged from 230 to 350 ml/hr. While a restriction of flow was

noticed in colums 3a and 3b, complete plugging did not occur. Column 3c

was provided with approximately three and one-half liters more of leachate

after the initial sample volume had been exhausted. The purpose for

adding the extra sample volume was to try to achieve saturation of the

carbon. Before the carbon could saturate, the column plugged and flow

dropped to less than 50 ml/hr. The shape of the data plot curve for

column 3c, shown in Figure 6, was similar to the shapes of the breakthrough curves for 3a and 3b. Duplication was not expected since the data from column 3a was assumed to be unrepresentative.

The effluent samples from columns 3b and 3c were collected, stored, and run through carbon columns in order to obtain comparison data for the data obtained from column 3a-Sub 1. The design of columns 3b-Sub 1 and 3c-Sub 1 was the same used for column 3a-Sub 1. The operational data unique to column 3b-2 were C_o = 8625 mg COD/1, liquid flow rate = 204 to 371 cm/hr, (.087 to .158 gal/min/ft^2) and retention time = 1.12 to 2.03 hrs. Table A-9 of Appendix A summarizes the column operational data.

The shape of data plot curve for column 3b-Sub 1, shown in Figure 7, was similar to that for 3a-Sub 1. However, the curve for 3b-2 developed a distinct dip or regression after the treatment of 3591 ml of leachate. The increase in adsorption (dip in C/Co ratio) appeared in the first sample during the fifth day following column set-up. In addition, the sample was stored at room temperature over its five-day collection time. In contrast, the majority of sample 3a-2 was refrigerated as it was collected. Therefore, the dip that occurred in curve 3b-2 was probably due to microbial action.

The operational data unique to sample 3c-2 was C_o = 9102 mg COD/1, liquid flow rate = 236 to 392 cm/hr, (.10 to .17 gal/min/ft^2), and retention time = 1.75 to 1.05 hrs. Table A-10 of Appendix A summarizes the column operational data. The shape of the data plot curve for 3c-Sub 1, shown in Figure 7 is similar to that for 3b-Sub 1.

As with sample 3b-Sub 1, sample 3c-Sub 1 was stored at room temperature
over its five-day collection time. In addition, the column sample
container for 3c-Sub 1 developed a leak and the sample remained in
the container for two days while the leak was repaired. Therefore,
the dip that occurred in curve 3c-Sub 1 was probably due to microbial
action.

BOD Test

The biochemical oxygen demand (BOD_5) test was used to indicate
the biodegradability of the organic matter present in the leachate.
In addition, because the composition of the organic matter present in
leachate changes with the age of the landfill, the BOD_5 test can be
used as an indicator of the age of the landfill. The decrease in the
BOD of landfill leachate with age can be correlated to the correspond-
ing decrease observed in the COD.[34] Therefore, the BOD_5 test can be
related to the COD test, thus establishing a check on the consistency
of analytical results.

In order to acclimate and to grow the leachate sample, it was
necessary to first grow a seed. Two reactors were started up as dis-
cussed in Chapter III. An initial food to microbe (F/M) ratio of 0.05/1
was established and gradually increased over a period of weeks. Although
neither reactor experienced serious difficulties, Reactor 2 ex-
perienced a reduction in MLSS when increased to an F/M ratio of
0.50/1. An F/M ratio of 0.25/1 was finally decided upon. There was
no attempt to optimize acclimation of the microbial population as this
was not the purpose of the reactors.

The total Kjeldahl nitrogen (TKN) test was used to measure the sum of the organic nitrogen and ammonia nitrogen in both reactors at feeding and at a time 24 hours after feeding. The intent of the testing was to demonstrate a lowering in the TKN value over a 24-hour period as an indication that nitrification was taking place. Nitrification would indicate that nitrifying bacteria were present and that stable microbial populations existed. The results of the TKN tests, summarized in Table A-11 of Appendix A, showed that the leachate feed contained very little organic and/or ammonia nitrogen, and essentially no nitrification process in Reactors 1 and 2. The TKN tests were performed again on supernatant from Reactor 2 after its use as a seed source for the BOD_5 tests with similar results.

Cook and Foree[45] reported the results of TKN tests they performed on samples from four batch reactors utilized in a study of the aerobic biostabilization of leachate. Based on their TKN results, they concluded that there was no evidence that nitrifying bacteria were present in Reactors 1 and 2, but that nitrifying bacteria were present in Reactors 3 and 4. The difference in their findings was attributed to the fact that Reactors 3 and 4 were given a daily 500 mg/l nitrogen supplement in the form of ammonia nitrogen while Reactors 1 and 2 were not. However, Cook and Foree concluded that the presence of nitrifying bacteria was not needed for successful aerobic biological treatment of leachate.

Since the microbial populations of both batch reactors in the experiment appeared healthy, (i.e., possessed good settling characteristics and a diverse microbial population when viewed under a microscope) the COD test was substituted for the TKN test to check for stabilization.

Samples of supernatant were withdrawn from both reactors just prior

to feeding, fifteen minutes after feeding (to allow aeration and mixing

of the feed), and twenty-four hours after feeding. The results of the

COD tests run on these samples showed a 91% reduction in Reactor 1 and

a 96% reduction in Reactor 2. The supernatant from Reactor 2 was chosen

as the seed source for the BOD_5 tests.

Four dilutions, .005, .01, .05, and 0.1 percent of leachate, were

used for the five-day BOD_5 test. The .05 and 0.1 percent dilutions

were checked for dissolved oxygen after two and one-half days. The

0.05 percent dilution samples required re-oxygenation to prevent them

from dropping below one part per million. The 0.1 percent dilution

samples had already dropped below one part per million by the time

checked. The .01 and .005 percent dilutions did not require re-oxygen-

ation and were considered more reliable. Table A-12 of Appendix A

summarizes the results of the BOD_5 tests. Table A-12 also includes

the results of the seed dilution BOD_5 tests.

The results of the five-day BOD tests show a mean value of 13,666

mg/l. The COD value of the leachate used in the tests was 17,480 mg/l

giving a BOD_5 to COD ratio of .78. Chain and DeWalle[34] in a study of

the BOD_5 to COD ratio versus the age of a landfill found a range of

0.8 to 0.048 within a time span of seventeen years, the higher ratios

corresponding to younger landfills.

Iron Tests

Chain and DeWalle[34] in their carbon column tests of high-strength

leachate (20,000 mg COD/l) reported a problem of head loss due to iron

precipitates. The precipitates were due to the oxidation of ferrous ions in the leachate to the ferric form. The latter then formed ferric hydroxide colloids which resulted in a brownish color precipitate. Since the carbon columns in the Chain and DeWalle[34] study were aerobic, it was felt that the use of anaerobic carbon columns would eliminate the problem of iron precipitation. However, plugging did occur in the anaerobic columns accompanied by a brownish color precipitate.

Although the carbon used to pack the anaerobic columns was dried prior to use, no attempt was made to drive out oxygen entrained in the carbon pores. The assumption was that the entrained oxygen would be found in the carbon used to line the landfill and therefore should be left in the carbon used for column testing. It was felt that the oxygen entrained in the pores of the carbon reacted with the ferrous iron in the leachate to form ferric hydroxide colloids. If so, precipitate should be high in iron content and the leachate should show a decrease in iron content after contact with the carbon column. Therefore, samples of raw leachate, column effluent, carbon with precipitate, and fresh carbon were tested for total iron using a Perkin-Elmer Atomic Absorption Spectrophotometer. The results of the iron analysis are shown in Table 11. Since there was no way to weigh the used carbon and the precipitate separately, it was not possible to accurately determine the ratio of iron to used carbon. However, the ratio of iron to used carbon and precipitate was 304.2 mg/1.0gm. The results of the above testing indicate that iron was precipitating out in the anaerobic carbon columns and causing plugging.

TABLE 11

IRON DETERMINATIONS

Sample	Iron Concentration
Raw Leachate	85.9 mg/1
Column Effluent	20.5 mg/1
Carbon with Precipitate	976.6 mg
Fresh Activated Carbon	25.2 mg/gm carbon

CHAPTER V

DISCUSSION OF RESULTS

The results of the study demonstrated the complex nature of young
leachate. Chapter V discusses the experimental results, offers possible
explanations for the behavior of the carbon/leachate system, and ex-
trapolates the findings to landfill design.

Carbon Adsorption Testing

A more detailed look at the equilibrium isotherms from Chapter IV
gives some insight into the complexity of leachate. The equilibrium
plots for leachate sample 3a are reproduced together in Figure 8 for
purposes of comparison. The slight difference in the results of the
equilibrium tests for sample 3a was due to the treatment of the carbon.
In performing the first equilibrium test, the carbon was pulverized
using a mortar and pestle and no care was taken to sieve it prior to
use. In performing the second equilibrium test, great care was taken
to pulverize and sieve the carbon. In sieving the carbon it was realized
that the carbon used in the first test must not have been well pulverized.

The plot of the results of the equilibrium tests apparently reflects
the difference in the size of the carbon particles. The results of
the second test shows a definite shift to the left. The shift results
in an X/M value of 2.45 for the second isotherm versus an X/M
value of 1.55 for the first at a C_o of 17.44. The greater X/M
value indicates the greater adsorptive capacity for the smaller carbon
particles.
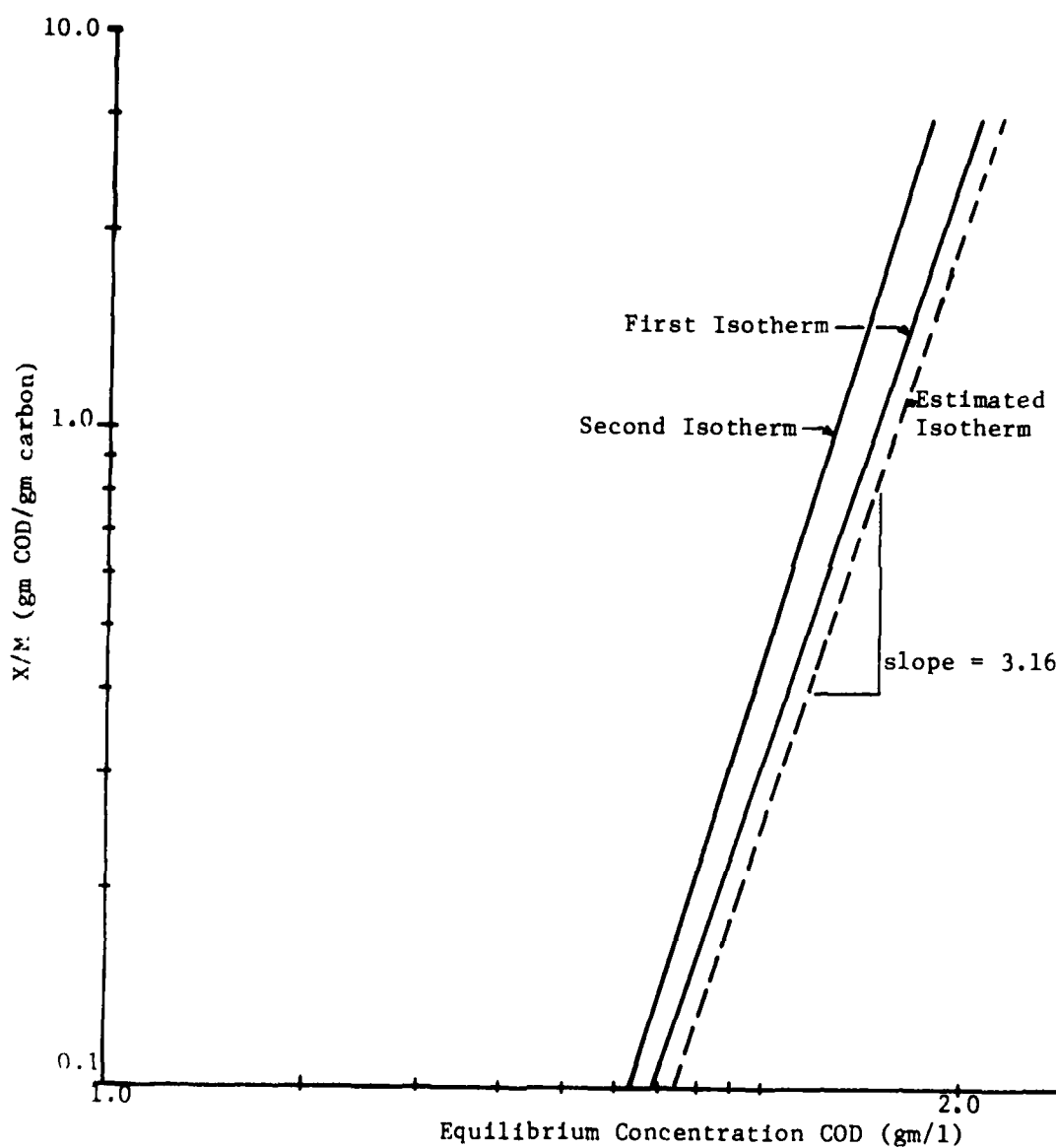
FIGURE 8. First, Second, and Estimated Equilibrium Isotherms, Leachate 3a.

Pulverizing carbon for use in equilibrium tests is recommended in the literature to increase the rate of adsorption and thus decrease the time necessary to complete the isotherm.[46] Pulverization is not considered to increase the surface area available for adsorption, the reason being that activated carbon contains numerous capillaries and the surface of the capillary (pore) walls is included in determining the available surface area for adsorption.[46] Pulverized carbon exposes the pore walls, making them more accessible to the adsorbate. Therefore, while pulverization increases the rate, it does not increase the surface area (and adsorption sites) and should not affect final equilibrium.

However, Figure 8 shows that pulverizing the carbon did affect final equilibrium in the tests with leachate. It was hypothesized that the long-chain, high molecular weight (molecular weight greater than 50,000), organic fraction of the leachate possessed the capacity to block granular carbon capillaries by their large size and/or configuration. Pulverizing the granular carbon reduced the blocking effect by exposing capillary walls. An estimated isotherm assuming similar carbon with reduced efficiency (indicated by a shift to the right) is shown by the dashed lines in Figure 8.

Another interesting feature of the equilibrium isotherms of Chapter IV is that they appear to change slope. The shift in slope would mean that the leachate contained at least two components which adsorbed at different rates with markedly different capabilities. The change in slope for the first equilibrium test performed on leachate sample 3a is shown by Figure 9. The possible change in

10.0

X/M (gm COD/gm carbon)

1.0

slope = 8.33

slope = 2.63

0.1

1.0   2.0   3.0

Equilibrium Concentration COD (gm/1)
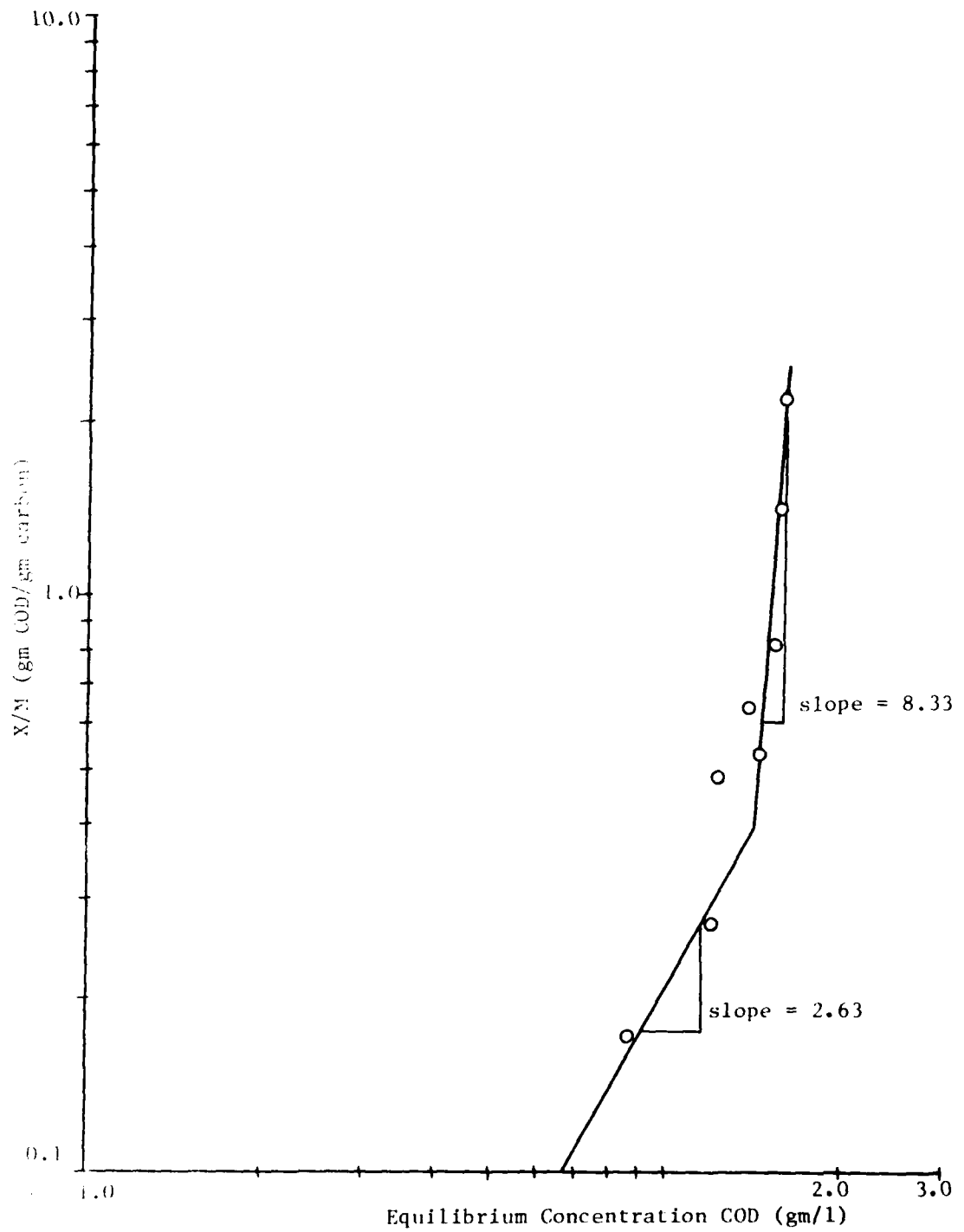
FIGURE 9.   First Equilibrium Isotherm, Showing Change of Slope

slope for the equilibrium test performed on leachate sample 4a is shown by Figure 10.

Based upon the slopes shown for both components of the isotherms of Figures 9 and 10 neither leachate component adsorbed well on activated carbon. Since the fraction of each component was unknown, it was impossible to determine how much each contributed to the COD of the leachate.

Carbon Column Tests

The theory of multi-component adsorption fits well into the analysis of the results achieved by carbon column testing. One of the things evidenced by the column tests was an initial effluent value of approximately 2000 mg COD/1. The initial value occurred in all columns tested, despite the fact that an equilization period between the leachate and carbon of over fifteen hours was allowed prior to drawing the first samples. The equilibrium test described in Chapter III was performed in order to determine if the initial COD value represented a non-adsorbable fraction or a poorly adsorbable fraction. Table A-13 of Appendix A summarizes the results of the equilibrium test. Figure 11 was a plot of the cumulative fraction of COD removed (expressed in grams per liter) versus the cumulative amount of carbon required (expressed in grams).

Figure 11 illustrates that practically all of the leachate COD was adsorbable. The flattening out of the adsorption equilibrium curve at its upper end indicates that some fraction of the COD was poorly adsorbable. The curve also shows that the equilibrium concentration became smaller with decreasing COD, again indicating leachate components
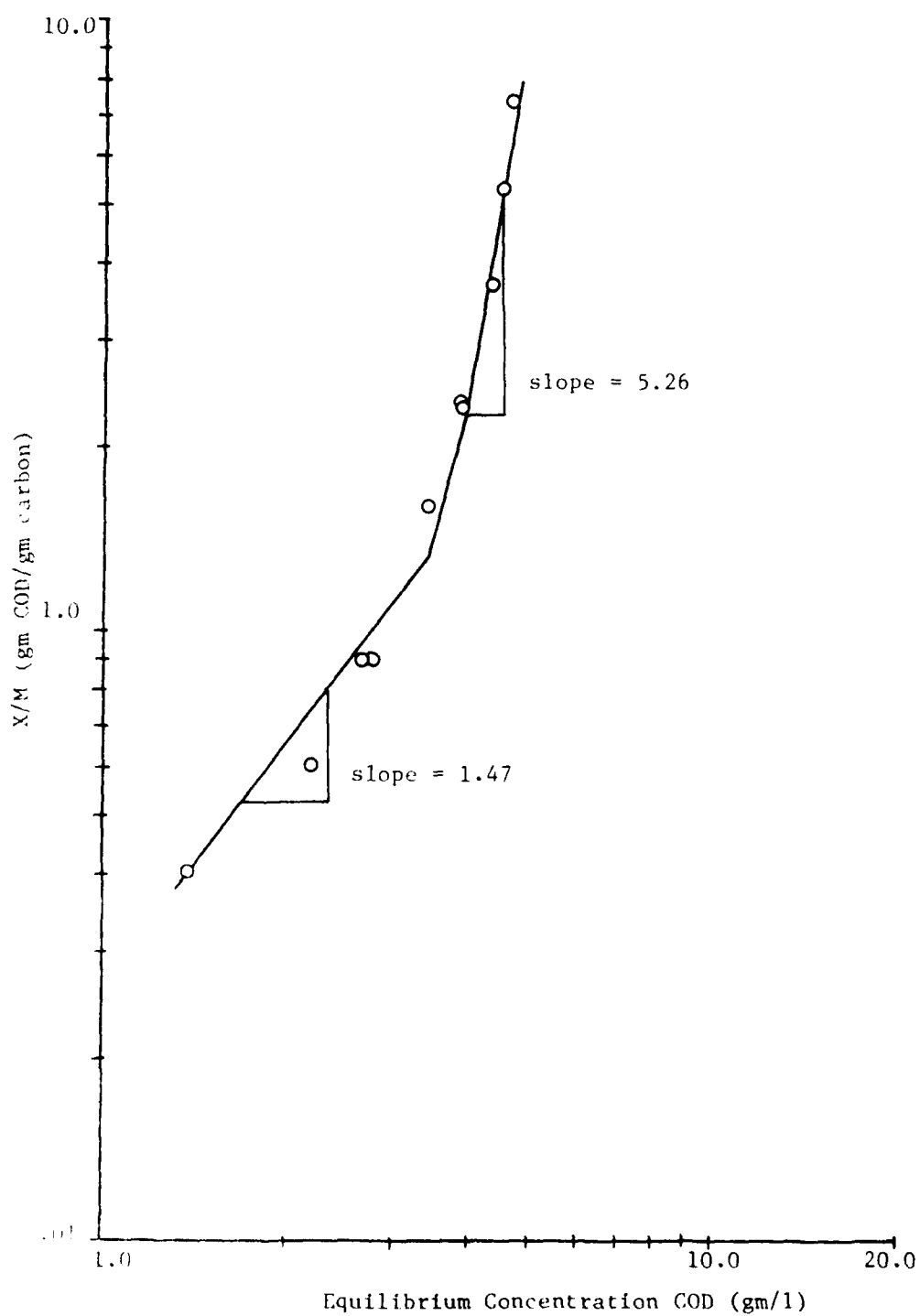
FIGURE 10. Third Equilibrium Isotherms, Showing Change of Slope.
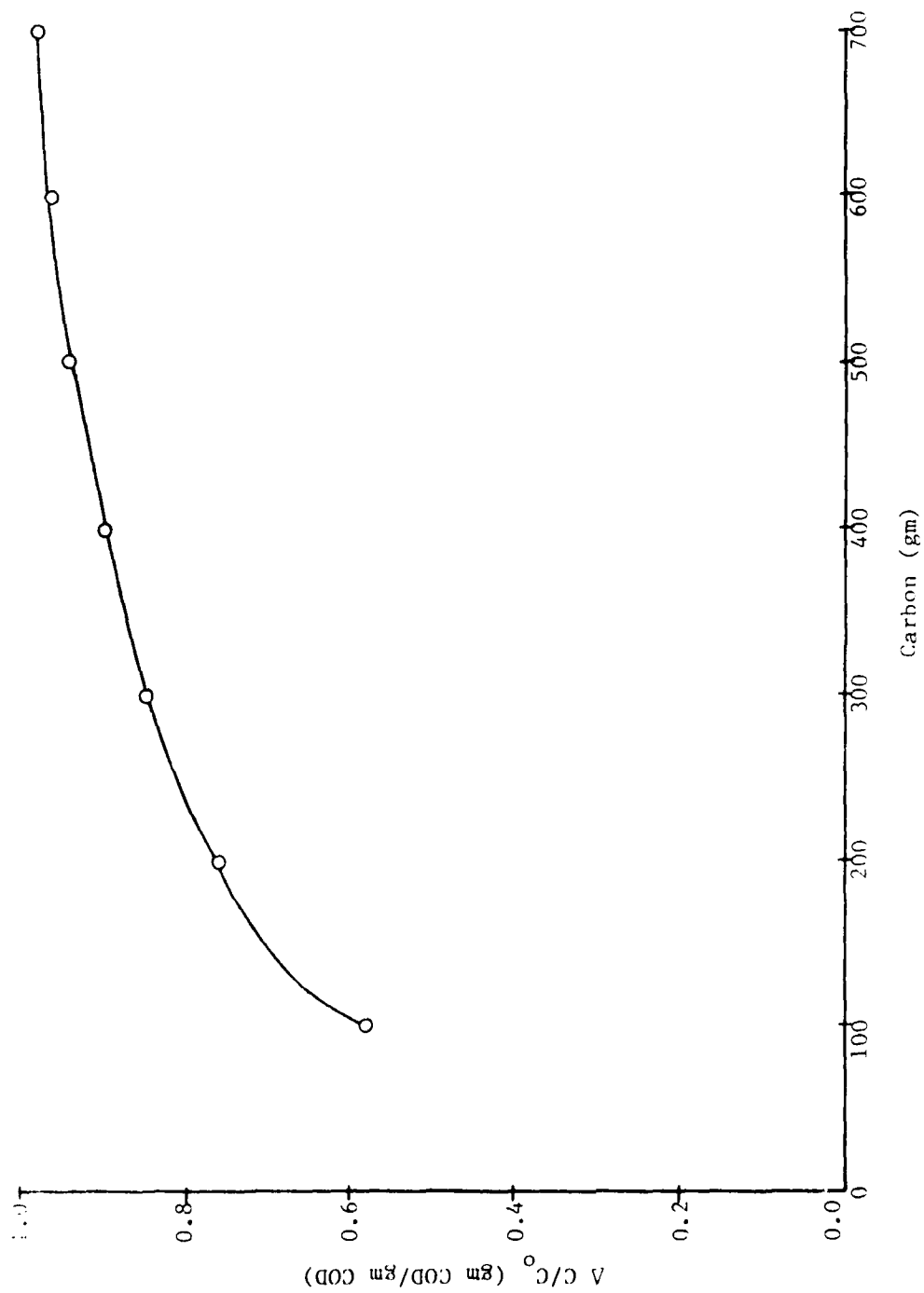
FIGURE 11. Equilibrium Isotherm to Determine Adsorbability.

Carbon (gm)

Δ C/C$_o$ (gm COD/gm COD)

with markedly different adsorption characteristics. One of the more

interesting bits of information illustrated by the curve is the large

amount of carbon required to reduce the initial COD value by 98 percent.

(It might be noted that a 98-percent reduction equates to a remaining

COD value of 327 mg/l).

The poorly adsorbable fraction could in part have accounted for

the initial COD value seen in the carbon column tests. Blocking of

the carbon pores as discussed previously could also have influenced

breakthrough. Another factor noted in multi-component samples is

competition for sites, which resulted in the displacement of previously

adsorbed (but less strongly held) components.[45] Thus, the poorly

adsorbed fraction could have been displaced from some sites and blocked

from others, resulting in the initial breakthrough observed.

The above factors also probably influenced the overall results

seen in the column tests. Figure 12 represents a composite

plot of the results of the first column tests. The plot shows that

the carbon column test results failed to yield the familiar S-shaped

curve of multi-component adsorption. None of the columns appeared

to reach saturation, but seemed to reach an equilibrium level at an

level of roughly 10.5 gm COD/l. The equilibrium condition

attributed to displacement, microbial action, and interaction

with iron.

The leachate appeared to be a multi-component adsorbate. It

likely that different leachate fractions competed for adsorption

It was just as likely that the carbon exhibited preferential

toward some fractions. The higher molecular weight fractions

leachate were not as readily adsorbed as were the lower weight
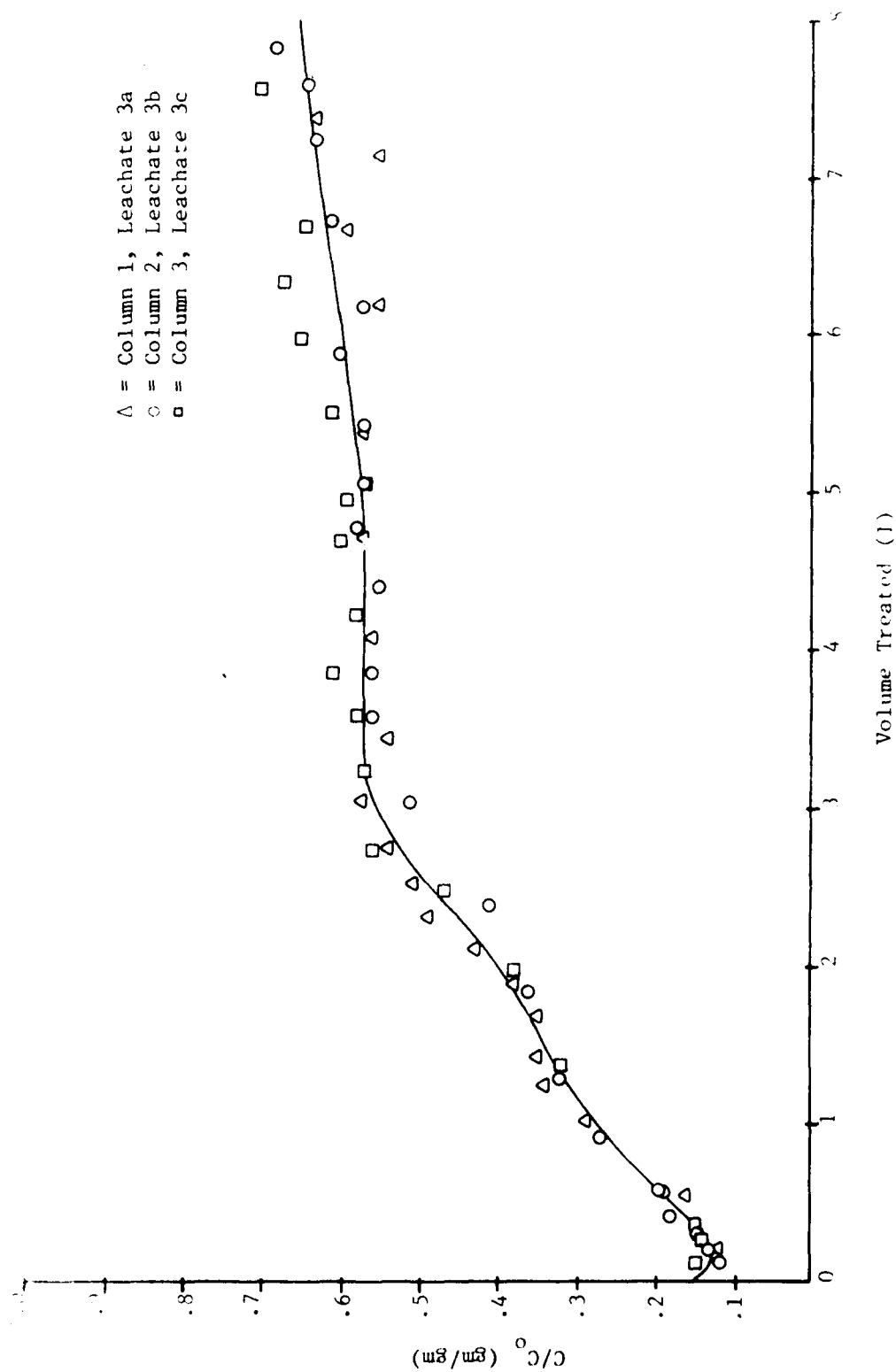
FIGURE 12. Composite Data Plot Curve for Second Column Tests

Volume Treated (1)

C/C$_o$ (gm/gm)

$\triangle$ = Column 1, Leachate 3a
$\circ$ = Column 2, Leachate 3b
$\square$ = Column 3, Leachate 3c

fractions. If the larger molecules blocked carbon capillaries during adsorption, a large area of adsorptive surface would be made unavailable. However, as larger molecules were displaced by smaller more adsorbable molecules, these areas would once more become available. The resultant continual regeneration would allow the carbon to maintain an equilibrium state with the feed leachate.

Microbial action could have influenced the results of the carbon columns, but it is not considered likely. Microbial action that had taken place during overnight column shut-down would have been evidenced by a measurable difference in shut-down and start-up column effluent COD. Although some decrease in effluent COD was noted occasionally during start-up, it was not enough to influence the results of the carbon column tests. Therefore, microbial action was not considered a significant factor in the results of the column tests on raw leachate.

Iron has the ability to interact with organic molecules and form chelates. Iron has shown a strong tendency to form chelates with the larger than 100,000 MW fraction of leachate.[35] The chelation of iron with large molecules coupled with its ability to form colloids and precipitate out in the column may well have played a large part in the equilibrium condition experienced in the columns. Chemical precipitation of young leachate has been reported to achieve a COD reduction of 0 to 50 percent.[35] Therefor, it is possible that as the iron precipitated it also removed a measurable fraction of COD from the leachate. Since the precipitation of iron is a chemical reaction it would have proceeded at a fixed rate based upon the column flow.

Because the results of the column tests on the raw leachate did not yield a familiar S-shaped plot, the effluent was collected for further column testing. The results of column test 3a-Sub 1 on the leachate are plotted on Figure 13. A line drawn through the plotted data points displays a more S-shaped curve.

The plot for leachate samples 3b-Sub 1 and 3c-Sub 1, Figure 7 (p. 55), shows a definite dip around 4.0 liters. The dip for both columns corresponds to a start-up period. Since both samples remained at room temperature for an extended period prior to testing, there was ample time for a microbial population to become established. Therefore the dip seen at 4.0 liters (start-up of the third day of testing) was attributed to microbial action. Due to the presence of microbial action in columns 3b-Sub 1 and 3c-Sub 1, their data plots were not considered representative. However, columns 3b-Sub 1 and 3c-Sub 1 were considered to support the data plot of column 3a-Sub 1 since the data plots for their first day of operation paralleled that of column 3a-Sub 1.

Although the shape of the curve obtained from column test 3a-Sub 1 was more familiar, the efficiency of this column in terms of COD removal was less than that of column test 3a. A reduced efficiency should be expected since the more adsorbable leachate fraction was stripped by column 3a. Column 3a, through preferential adsorption, separated the leachate fractions with the more poorly adsorbable and least competitive leachate fractions comprising the majority of the column effluent. As a result, the feed for column 3a-Sub 1 test was more homogeneous. The homogenous nature of the feed would also explain the more S-shaped curve since the S-shape adsorption curve has been shown to be associated with single component adsorbate or multi-component adsorbates when all the
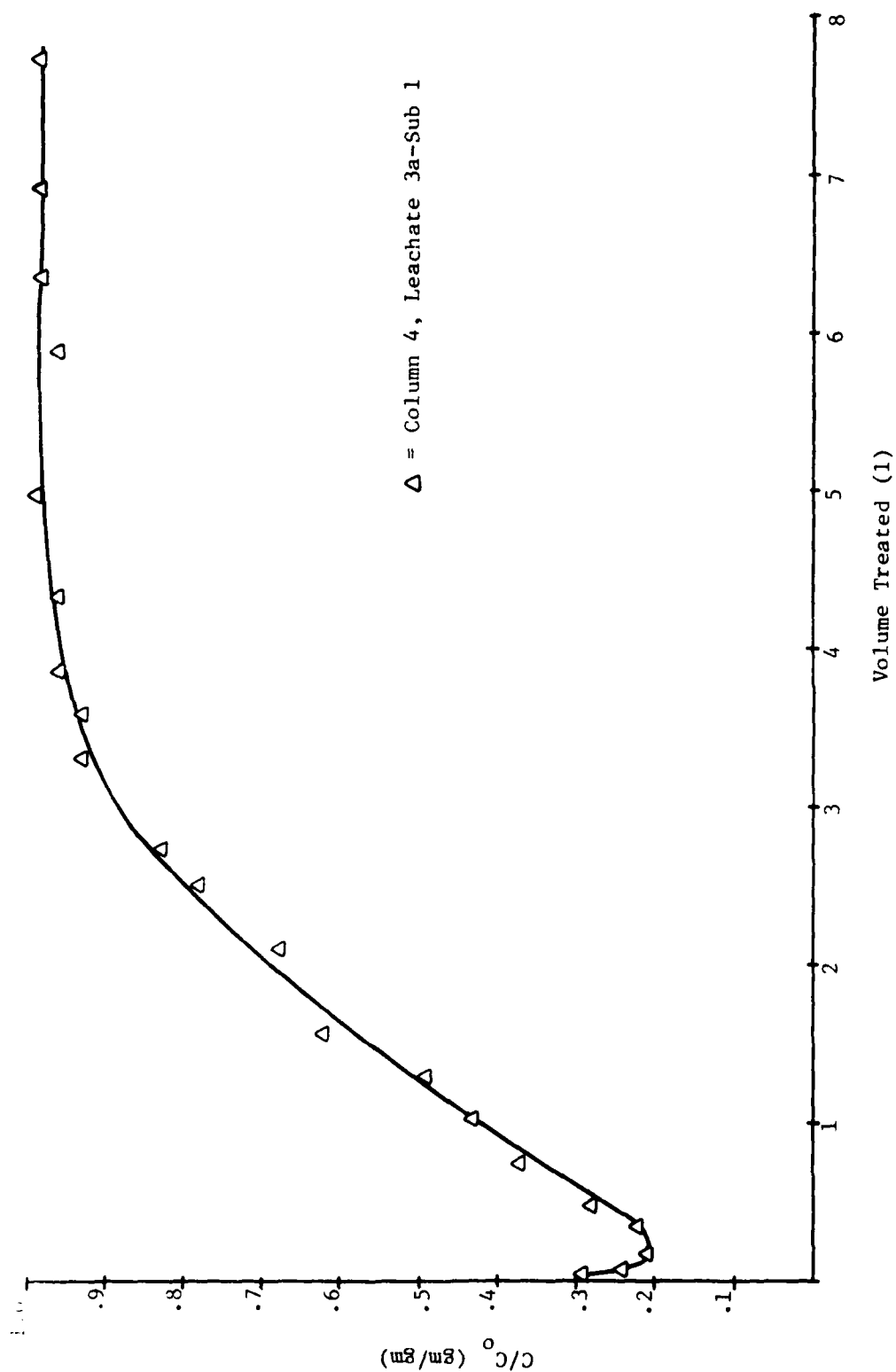
FIGURE 13. Composit Data Plot Curve for Second Column Test 3a-Sub 1.

$\triangle$ = Column 4, Leachate 3a-Sub 1

Volume Treated (1)

C/C_o (gm/gm)

species present are adsorbed equally.[46]

Efficiency of Carbon

The efficiency of the carbon in removing leachate contaminants from water was determined by using the adsorption isotherms and the results from the first column tests. The isotherm from the first equilibrium test along with the estimated isotherm (Figure 8, p. 64) were used in determining carbon efficiency. From Figure 11 (p. 69) it appears that equilibrium was reached at C/C_o ratio of 0.58. Multiplying an averaged COD value (from the three column feed COD's) of 17.44 gm COD/l, by the equilibrium ratio yields a value of 10.12 gm COD/l. Entering Figure 8 (p. 64) at the equilibrium concentration, efficiencies of 0.34 from the first isotherm and .26 from the estimated isotherm are obtained.

The carbon efficiency was calculated by adding up the area under the curve for the first column tests. Table A-14 of Appendix A summarizes the addition of the curve area. The results of the addition yielded 69.682 grams/COD removed by 200 grams of carbon for an efficiency of 0.35. The efficiency found using the column tests results was similar to the efficiency found using the first isotherm. It was greater than the efficiency found using the theoretical isotherm.

The efficiency of the carbon in adsorbing contaminants from the effluent of the first columns was determined by using the results from column test 3a-Sub 1. The carbon efficiency was calculated by summing the area under the curve for the column test 3a-Sub 1. Table A-15 of Appendix A summarizes the addition of the curve area. The results of the addition yielded an efficiency of 0.12.

If column test 3a-Sub 1 is considered to have been run in series with the first column tests the overall efficiency changed. The above assumption could be made because it did not significantly affect the total amount of COD removed by the carbon. There is a possibility that if the columns had been run in series, the resultant data plot curve would have changed. Therefore, by adding up the total COD removed by both column tests and dividing by the total carbon for two columns an efficiency of 0.24 was obtained. This efficiency is similar to the efficiency found using the estimated isotherm.

Interpretation of Results

The results of the testing were applied to the study objective of determining the feasibility of using activated granular carbon to control initial (stage 1 and stage 2) leachate. The leachate used in the study was young leachate having an average COD value of 17.440 mg/l. Initial leachate, however, has a COD value of approximately 50,000 mg/l.[18,34] Fungaroli[18] reported an initial leachate production of 8.547 liters in simulated landfills having a diameter of 1.83 meters (m) (2.00 yards) and a 2.44 m (2.67 yards) thick refuse layer, with a compaction ratio of 2:1. By dividing the volume of refuse in cubic meters (yards) into the volume of initial leachate produced, a value of 1.33 liters initial leachate per cubic meter (1.02 1/cubic yard) of refuse is obtained. Assuming an overall carbon efficiency of 0.24 per previous discussion, the following mathematical calculation yields the grams of carbon required:

$$1.33 \ 1/m^3 \times 50 \ gmCOD/1 \times 1/.24 = 277.08 \ gm/m^3$$

(A similar calculation utilizing English units yielded
212.39 gm/yd^3.)

The carbon used in this study had a measured density of 0.48 gm/
cubic centimeter (7.9 gm/in^3). Therefore, using the study carbon to
control initial leachate would require a depth of 0.058 cm carbon/m^3
(0.021 in/ft^3) of refuse. Assuming a 4.57-m (5-yd) layer of refuse
and 100% adsorption, approximately 0.27 cm (.11 inch) linning of acti-
vated granular carbon would be required to control initial leachate.[27]

It should be noted that the use of activated granular carbon in
landfill construction would not prevent leachate pollution. The carbon
column tests showed that the leachate sample possessed a poorly adsorb-
able COD portion equal to approximately 11.5 percent of its initial
COD value. Extrapolating the study results to initial leachate COD
would yield 5,750 mg COD/1. Whether or not 5,750 mg COD/1 leachate
in the small quantities expected to be generated (per Fungaroli's[18]
study) would present a significant potential problem was not addressed
in this study.

It is recommended that studies be conducted to determine the rate
of initial leachate generation and its effect on COD adsorption. The
possibility that slow production of initial leachate and resulting extended
contact time would effect COD adsorption should be investigated. Weber
and Morris[47] found that some molecules require several weeks of continual
contact to achieve adsorption. The possibility of microbial action

on the leachate COD also should be investigated. In addition, studies

should be conducted into the effect sealing a landfill has on leachate

production.

Comparison of Carbon Results to Clay Soil

The study would not have been complete without comparing carbon

adsorption of leachate to that of clay soils. Clay soils deserved

consideration because they are perhaps the most widely used liner

material in the United States. Unfortunately, like many other aspects

of solid waste, data concerning COD attenuation by clay soils are

extremely limited. While four studies concerning the attenuation of

heavy metals by clay soils were found, only one study was found con-

cerning the attenuation of COD. Griffin and Shimp[48] passed leachate

through columns containing various clay mixtures and measured the effluent

leachate concentrations. They plotted their results as relative con-

centration versus pore fraction. Pore volume is defined as the liquid

volume of the column. The pore fraction represents the cumulative volume

of column effluent divided by the column pore volume.

From their results, Griffin and Shimp[48] determined relative attenua-

tion numbers (ATN). The ATN was obtained by summing the area under

the plotted data curves, subtracting it from the total area, and then

expressing it as a percentage. The equivalent procedure for this study

was to add up the total COD removed by the first carbon columns [area

under the curve of Figure 12(p. 71)] and subtract the value found from

the total leachate COD that had passed through the columns, and divide

that value by the total COD. Table 12 shows the ATN number calculated

for carbon versus ATN numbers reported for various clay minerals by

Griffin and Shimp[48].

TABLE 12

MEAN ATTENUATION NUMBER (ATN) OF COD
FOUND IN MUNICIPAL LEACHATE FOR ACTIVATED
CARBON AND THREE CLAY MINERALS

Parameter	Activated Carbon	Montmorillonite	Illite	Kaolinite
COD	50.1	24.6	23.2	16.2

The above table indicates that activated carbon is almost twice

as effective in removing COD from leachate as any of the clay minerals

tested. Therefore, the use of activated carbon may be preferable in

situations where clay soils are difficult to obtain.

CHAPTER VI

CONCLUSIONS

The results of the literature search conducted indicated that the use of water impermeable covers to prevent stage-3 (long-term) leachate production may be a feasible design method. The literature search also indicated that the composition of municipal refuse is expected to change, but that the change should not result in a decrease in the production of stage-1 and-2 (initial) leachate. The results of the study indicated that the use of granular activated carbon may be feasible for the control of stage-1 and-2 (initial) leachate.

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APPENDIX A

AD-A108 302   AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH   F/G 13/2
                USE OF IMPERVIOUS COVERS AND CARBON ADSORPTION FOR THE CONTROL --ETC(U)
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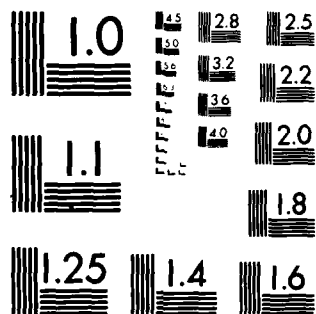
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

TABLE A-1

RESULTS OF RATE OF ADSORPTION TESTS, LEACHATE 3a

Time (hrs)	COD (mg/1)	% Adsorbate Remaining in Liquid
0.0	16,675	100.0
0.5	12,738	76.4
1.0	12,159	72.9
2.0	12,429	74.5
3.0	12,429	74.5
4.0	12,198	73.2

TABLE A-2

RESULTS OF FIRST EQUILIBRIUM TESTS, LEACHATE 3a

Sample #	Mass of Carbon M (gm/1)	Initial Conc Co (gm/1)	Equilibrium Conc C* (gm/1)	C X (gm/1)	Adsorption Ratio X/M (gm/gm)
1	0.5	16.934	15.837	1.097	2.19
2	1.0	16.934	15.523	1.411	1.41
3	2.0	16.934	15.288	1.646	0.82
4	5.0	16.934	14.269	2.665	0.53
5	5.0	16.934	13.720	3.214	0.64
6	10.0	16.934	12.152	4.782	0.48
7	25.0	16.934	10.192	6.742	0.27
8	25.0	16.934	10.192	6.742	0.27
9	50.0	16.934	8.546	8.388	0.17
10	50.0	16.934	8.565	8.369	0.17
11	100.0	16.934	6.723	10.211	0.10

TABLE A-3

RESULTS OF SECOND EQUILIBRIUM TESTS, LEACHATE 3a

Sample #	Mass of Carbon M (gm/1)	Initial Conc Co (gm/1)	Equilibrium Conc C* (gm/1)	C X (gm/1)	Adsorption Ratio X/M (gm/gm)
1	2.0	16.675	13.896	2.779	1.39
2	2.0	16.675	13.433	3.242	1.62
3	5.0	16.675	12.429	4.246	0.85
4	10.0	16.675			
5	10.0	16.675	10.885	5.790	0.58
6	25.0	16.675	9.418	7.257	0.29
7	50.0	16.675	7.643	9.032	0.18
8	50.0	16.675	7.990	8.685	0.17
9	100.0	16.675	6.080	10.595	0.11

TABLE A-4

RESULTS OF THIRD EQUILIBRIUM TESTS, LEACHATE 4a

Sample #	Mass of Carbon M (gm/1)	Initial Conc Co (gm/1)	Equilibrium Conc C* (gm/1)	C X (gm/1)	Adsorption Ratio X/M (gm/gm)
1	0.5	5.000	4.636	0.364	.73
2	1.0	5.000	4.471	0.529	.53
3	2.0	5.000	4.253	0.747	.37
4	5.0	5.000	3.870	1.130	.23
5	5.0	5.000	3.793	1.207	.24
6	10.0	5.000	3.372	1.628	.16
7	25.0	5.000	2.759	2.241	.09
8	25.0	5.000	2.682	2.318	.09
9	50.0	5.000	2.192	2.808	.06
10	100.0	5.000	1.379	3.621	.04

TABLE A-5

OPERATIONAL DATA FOR CARBON COLUMN TESTS, LEACHATE 3a

Volume Passed (1)	Initial Conc.-Co (gm/1)	Effluent COD-C (gm/1)	C/Co (gm/gm)
0.175	17.740	2.128	0.12
0.525	17.740	2.888	0.16
1.006	17.740	5.130	0.29
1.225	17.740	6.029	0.34
1.400	17.740	6.201	0.35
1.453	17.740	5.991	0.34
1.666	17.740	6.182	0.35
1.879	17.740	6.735	0.38
2.092	17.740	7.594	0.43
2.305	17.740	8.643	0.49
2.508	17.740	9.006	0.51
2.721	17.740	9.654	0.54
3.040	17.740	10.074	0.57
3.416	17.740	9.540	0.54
4.060	17.740	9.918	0.56
4.704	17.740	10.070	0.57
5.073	17.740	10.070	0.57
5.389	17.740	10.032	0.57
6.178	17.740	9.813	0.55
6.650	17.740	10.410	0.59
7.122	17.740	9.813	0.55
7.358	17.740	11.120	0.63

TABLE A-6

OPERATIONAL DATA FOR CARBON COLUMN TESTS, LEACHATE 3a-Sub 1

Volume Passed (1)	Initial Conc.-Co (gm/1)	Effluent COD-C (gm/1)	C/Co (gm/gm)
0.025	8.892	2.558	0.29
0.070	8.892	2.122	0.24
0.161	8.892	1.888	0.21
0.342	8.892	1.934	0.22
0.472	8.892	2.512	0.28
0.750	8.892	3.401	0.37
1.022	8.892	3.822	0.43
1.294	8.892	4.329	0.49
1.566	8.892	5.499	0.62
2.110	8.892	6.045	0.68
2.518	8.892	6.903	0.78
2.755	8.892	7.410	0.83
3.315	8.892	8.268	0.93
3.592	8.892	8.229	0.93
3.875	8.892	8.561	0.96
4.340	8.892	8.541	0.96
4.960	8.892	8.763	0.99
5.890	8.892	8.541	0.96
6.355	8.892	8.756	0.98
6.820	8.892	8.678	0.98
7.220	8.892	8.717	0.98

TABLE A-7

OPERATIONAL DATA FOR CARBON COLUMN TESTS, LEACHATE 3b

Volume Passed (1)	Initial Conc.-Co (gm/1)	Effluent COD-C (gm/1)	C/Co (gm/gm)
0.100	17.480	2.152	0.12
0.175	17.480	2.251	0.13
0.300	17.480	2.705	0.15
0.400	17.480	3.205	0.18
0.550	17.480	3.339	0.19
0.600	17.480	3.473	0.20
0.900	17.480	4.656	0.27
1.269	17.480	5.665	0.32
1.823	17.480	6.354	0.36
2.376	17.480	7.226	0.41
3.022	17.480	8.853	0.51
3.575	17.480	9.816	0.56
3.852	17.480	9.807	0.56
4.406	17.480	9.693	0.55
4.775	17.480	10.151	0.58
5.055	17.480	9.933	0.57
5.428	17.480	10.036	0.57
5.895	17.480	10.510	0.60
6.175	17.480	9.922	0.57
6.735	17.480	10.903	0.61
7.225	17.480	11.028	0.63
7.575	17.480	11.128	0.64
7.806	17.480	11.906	0.68
8.384	17.480	11.830	0.68
8.557	17.480	11.639	0.67

TABLE A-8

OPERATIONAL DATA FOR CARBON COLUMN TESTS, LEACHATE 3c

Volume Passed (1)	Initial Conc.-Co (gm/l)	Effluent COD-C (gm/l)	C/Co (gm/gm)
0.102	17.100	2.553	0.15
0.205	17.100	2.406	0.14
0.341	17.100	2.538	0.15
0.853	17.100	3.938	0.23
1.364	17.100	5.393	0.32
1.961	17.100	6.499	0.38
2.472	17.100	8.051	0.47
2.728	17.100	9.661	0.56
3.240	17.100	9.739	0.57
3.580	17.100	9.855	0.58
3.855	17.100	10.360	0.61
4.222	17.100	9.972	0.58
4.680	17.100	10.204	0.60
4.955	17.100	10.010	0.59
5.505	17.100	10.360	0.61
5.986	17.100	11.174	0.65
6.330	17.100	11.485	0.67
6.680	17.100	10.980	0.64
7.555	17.100	11.983	0.70
8.605	17.100	12.218	0.71
8.868	17.100	13.001	0.76
9.098	17.100	12.218	0.71
9.328	17.100	13.001	0.76
9.558	17.100	12.688	0.74
9.903	17.100	13.158	0.77
10.363	17.100	12.727	0.74
10.739	17.100	11.787	0.69
10.958	17.100	11.748	0.69
11.131	17.100	12.610	0.74
11.303	17.100	12.414	0.73
11.347	17.100	12.453	0.73
11.399	17.100	12.923	0.76

TABLE A-9

OPERATIONAL DATA FOR CARBON COLUMN TESTS, LEACHATE 3b-Sub1

Volume Passed (1)	Initial Conc.-Co (gm/1)	Effluent COD-C (gm/1)	C/Co (gm/gm)
0.050	8.625	1.430	0.17
0.150	8.625	1.391	0.16
0.240	8.625	1.313	0.15
0.340	8.625	1.656	0.19
0.612	8.625	2.735	0.32
0.986	8.624	3.750	0.43
1.428	8.625	5.355	0.62
1.676	8.625	4.883	0.57
1.965	8.625	5.196	0.59
2.296	8.625	5.391	0.63
2.668	8.625	7.110	0.82
3.226	8.625	6.836	0.79
3.591	8.625	3.828	0.44
4.199	8.625	5.335	0.62
.....	8.625	6.680	0.77
.....	8.625	7.442	0.86
5.781	8.625	8.164	0.95
6.329	8.625	8.150	0.94
6.700	8.625	8.465	0.98

TABLE A-10

OPERATIONAL DATA FOR CARBON COLUMN TESTS, LEACHATE 3c-Sub 1

Volume Passed (1)	Initial Conc.-Co (gm/1)	Effluent COD-C (gm/1)	C/Co (gm/gm)
0.075	9.102	1.906	0.21
0.150	9.102	1.750	0.19
0.236	9.102	1.516	0.17
0.511	9.102	1.438	0.16
0.826	9.102	2.793	0.31
1.141	9.102	5.449	0.60
1.711	9.102	5.352	0.59
1.861	9.102	5.391	0.59
2.305	9.102	5.938	0.65
2.661	9.102	7.149	0.79
3.061	9.102	7.735	0.85
3.461	9.102	8.086	0.89
3.861	9.102	8.047	0.88
4.214	9.102	5.788	0.64
4.832	9.102	6.890	0.76
5.273	9.102	7.363	0.81
5.803	9.102	7.638	0.84
6.509	9.102	8.780	0.96
6.901	9.102	7.914	0.87
7.489	9.102	8.111	0.89

TABLE A-11

RESULTS OF TOTAL KJELDAHL NITROGEN TESTS

Reactor #	Sample*	First Tests[+] Results (mg/l)	Second Tests[‡] Results (mg/l)
1	1	22.54	
1	2	17.22	
1	3	18.90	
1	4	19.30	
2	1	18.75	1.70
2	2	15.50	2.00
2	3	15.00	
2	4	15.75	2.00

*Sample 1 - Taken before feeding
 Sample 2 - Taken immediately after feeding
 Sample 3 - Taken 16 hours after feeding
 Sample 4 - Taken 24 hours after feeding

[+]Sample used was MLSS from reactor

[‡]Sample used was supernatant from reactor

TABLE A-12

RESULTS OF BODs TESTS

Sample	Dilution	BODs (gm/1)	D.O.
Raw Leachate	0.1%	--	
"	0.1%	--	
"	0.1%	--	
"	0.5%	11.500	
"	0.5%	11.500	
"	0.5%	13.900	
"	0.01%	15.000	
"	0.01%	17.000	
"	0.01%	23.000	
"	0.005%	13.000	
"	0.005%	9.000	
"	0.005%	9.000	
1st Effluent	.5%	--	
	.5%	--	
	.1%	5000	
	.1%	4900	
Seed	2/300 ml		1.5
"	2/300 ml		1.5
"	3/300 ml		2.3
"	3/300 ml		2.8
"	4/300 ml		3.0
"	4/300 m.		3.5

TABLE A-13

ADSORBABLE FRACTION EQUILIBRIUM TEST, LEACHATE 3a

Sample	Carbon		Co	C*	ΔC	Cumulative	ΔC/Co
Run #	Per Run (gm/1)	Cumulative (gm/1)	(gm/1)	(gm/1)	(gm/1)	ΔC (gm/1)	
1	100	100	17.100	9.217	9.883	9.883	0.58
2	100	200	7.217	4.171	3.046	12.929	0.77
3	100	300	4.171	2.567	1.604	14.533	0.85
4	100	400	2.567	1.675	0.892	15.425	0.90
5	100	500	1.675	1.099	0.576	16.001	0.94
6	100	600	1.097	0.640	0.459	16.460	0.96
7	100	700	0.640	0.313	0.327	16.787	0.98

TABLE A-14

AREA UNDER THE CURVE, FIRST COLUMN TESTS

Volume Treated (1)	Average C/Co (gm/gm)	Co (gm/1)	COD Effluent (gm)	COD Removed (gm)
0.00 - 0.15	.14	17.440	0.366	2.250
0.50 - 0.50	.16	17.440	0.976	5.128
0.50 - 1.00	.23	17.440	2.006	6.714
1.00 - 1.50	.31	17.440	2.703	6.017
1.50 - 2.00	.38	17.440	3.314	5.406
2.00 - 2.50	.45	17.440	3.924	4.796
2.50 - 3.00	.53	17.440	4.622	4.098
3.00 - 3.25	.57	17.440	2.485	1.875
3.25 - 4.75	.57	17.440	14.910	11.250
4.75 - 5.50	.58	17.440	7.587	5.493
5.50 - 6.00	.59	17.440	5.145	3.575
6.00 - 7.00	.61	17.440	10.640	6.800
7.00 - 8.00	.64	17.440	11.160	6.280
		Total	69.838	69.682

TABLE A-15

AREA UNDER THE CURVE, SECOND COLUMN TESTS

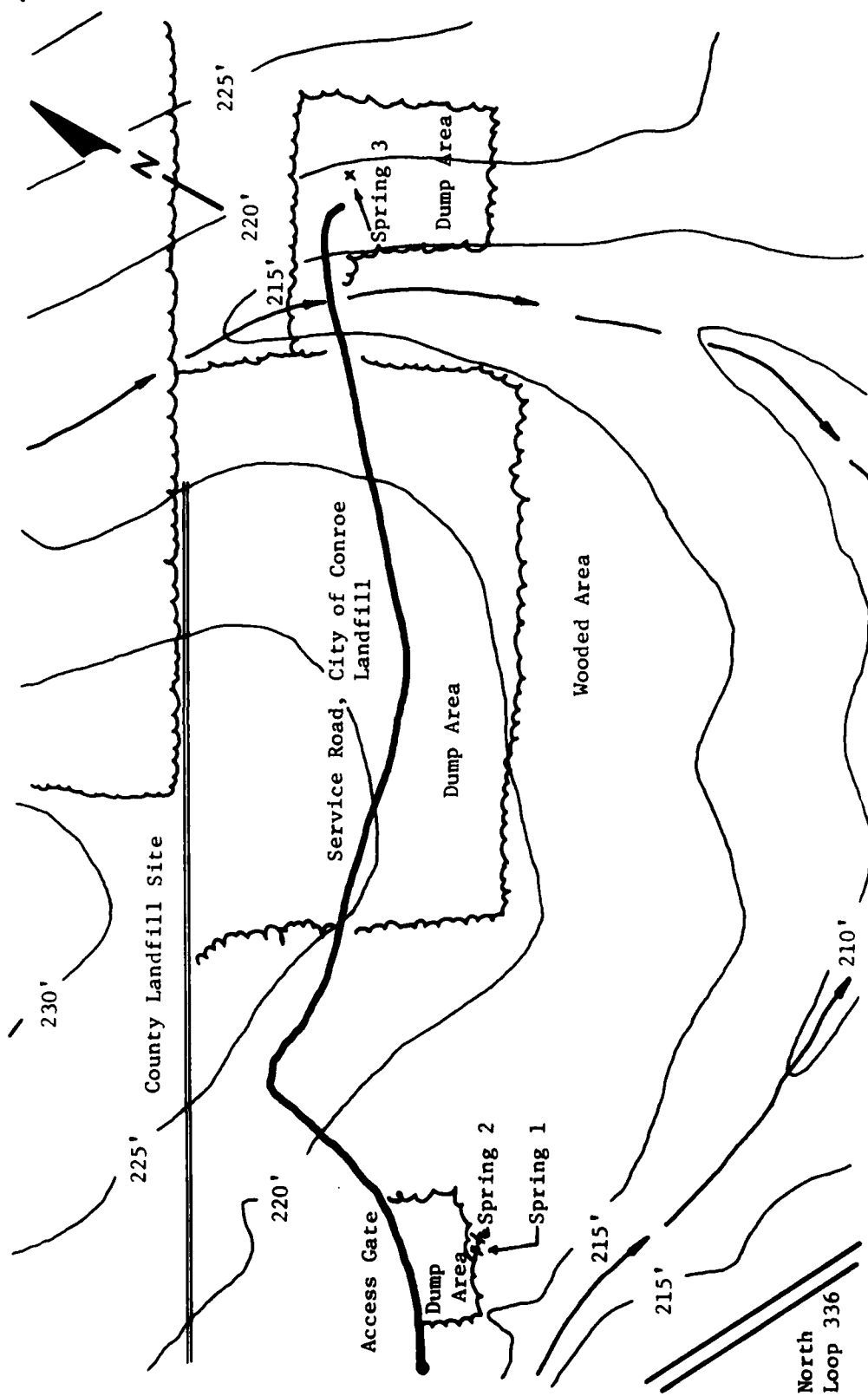| Volume Treated	Average C/Co	Co	COD	
(1)	(gm/gm)	(gm/1)	Effluent (gm)	Removed (gm)
0.00 – 0.200	.20	8.873	.355	8.518
0.200– 1.00	.28	8.873	1.988	6.885
1.00 – 2.00	.46	8.873	4.082	4.791
2.00 – 3.00	.74	8.873	6.566	2.307
3.00 – 4.00	.88	8.873	7.808	1.065
4.00 – 5.00	.94	8.873	8.341	.532
5.00 – 6.00	.96	8.873	8.518	.355
6.00 – 8.00	.97	8.873	8.607	.266
		Total	46.265	24.719

APPENDIX B

FIGURE B-1. City of Conroe, Texas Landfill Site.

VITA

Richard Charles Carmichael
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BACKGROUND: Born on 26 June 1945 in Alexandria, Louisiana of Colonel
(ret) Jack C. Carmichael and Doris E. Carmichael.
Graduated from Bethesda-Chevy Chase High School, Beth-
esda, Maryland in 1963, attended Texas A & M University
from 1963 to 1964, transferred to The University of Texas
at Austin, received a Bachelor of Science degree in
Architectural Engineering in 1968.

PROFESSIONAL   Entered the United States Air Force (USAF) in
EXPERIENCE: August 1968, in July 1969, was transferred to the
Biomedical Sciences Corps USAF as a Bioenvironmental
Engineer. Assignments include: Chief of Bioenviron-
mental Engineering Occupational Medicine, and Military
Public Health for Beale Air Force Base (AFB), California,
July 1969 to July 1971: Regional Bioenvironmental
Engineer, Military Regions I and II, Republic of South
Vietnam, August 1971 to June 1972, with consulting
responsibilities to U.S. Army and Republic of South
Vietnam Air Force Installations; Bioenvironmental
Engineer, USAF Hospital Takhli, Takhli Royal AFB, Thailand,
from July 1972 to August 1972, during the reactivation
of the base by U.S. forces; Chief, Environmental Health
Services, David Grant USAF Medical Center, Travis AFB,
California, August 1972 to August 1977; and from Sep-
tember 1977 to December 1978 Air Force Institute of
Technology student, Texas A & M University, Texas.